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Abstract: The report provides a general introduction to the climate change issue and reviews selected previous studies. It discusses the greenhouse gases, their sources and sinks, chemical properties, current atmospheric concentrations and distributions, and related uncertainties and relates the greenhouse gases to the processes of climatic change. Once this link is made the report examines those human activities that affect trace-gas emissions and ultimately influence climate change. It discusses the scenarios developed to assist in thinking about possible future emissions and climate change and then presents sensitivity analyses of the modeling results. The report gives a detailed description of existing and emerging technologies that should be considered in the formulation of a comprehensive strategy for mitigating global warming, outlines domestic policy options, and discusses international mechanisms for responding to climate change.

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POLICY OPTIONS FOR STABILIZING GLOBAL CLIMATE

DRAFT

REPORT TO CONGRESS

Volume I: Chapters I-VI

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation

February 1989

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Volume I: Chapters I-VI

Editors: Daniel A. Lashof and Dennis A. Tirpak

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation

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DISCLAIMER

This draft is being circulated for review and comment and does not necessarily reflect the official position of the U.S. Environmental Protection Agency. Mention of trade names does not constitute an endorsement.

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  I. Uncertainties regarding climatic change are large, but there is a growing consensus in the scientific community that significant global warming due to anthropogenic greenhouse gas emissions is probable over the next century, and that rapid climatic change is possible. 83

  II. Measures undertaken to limit greenhouse gas emissions would decrease the magnitude and speed of global warming, regardless of uncertainties about the response of the climate system. 85

  III. No single country or source will contribute more than a fraction of the greenhouse gases that will warm the world; any overall solution will require cooperation of many countries and reductions in many sources. 87

  IV. A wide range of policy choices is available to reduce greenhouse gas emissions while promoting economic development, environmental, and social goals. 89

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INTRODUCTION

The Earth's Climate and Global Change

The greenhouse effect is a natural phenomenon that plays a central role in determining the Earth's climate. Sunlight passes through the atmosphere and warms the Earth's surface. The Earth then radiates infrared energy, some of which escapes back into space. But certain gases (known as greenhouse gases) that occur naturally in the atmosphere absorb most of the infrared radiation and emit some of this energy back toward the Earth, warming the surface. This effect is, to a great extent, responsible for making the Earth conducive to life. In its absence, the Earth would be approximately 30°C colder.

Concerns about the greenhouse effect arise out of apprehension that anthropogenic (man-made) emissions of greenhouse gases will further warm the Earth. Greenhouse gases -- primarily carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and tropospheric ozone (O_3) -- are produced as by-products of human activities. When these gases are emitted into the atmosphere and their concentrations increase, the greenhouse effect is compounded. The result is an increase in mean global temperatures.

There is scientific consensus that increases in greenhouse gas emissions will result in climate change (Bolin et al., 1986; NAS, 1979, 1983, 1987; WMO, 1985). The Council on Environmental Quality concluded in 1981 that the potential long-term risks of societal disruption caused by increased atmospheric concentrations of CO_2 (aside from the other greenhouse gases) are significant. However, considerable uncertainty exists with regard to the ultimate magnitude of the warming, its timing, and the regional patterns of change. In addition, there is great uncertainty about changes in climate variability and regional impacts.

CONGRESSIONAL REQUEST FOR REPORTS

EPA has studied the effects of global warming for several years. The goal of its efforts has been to use the best available information and models to assess the effects of climatic change and to evaluate policy strategies for both limiting and adapting to such change.

In 1986, Congress asked EPA to develop two reports on global warming. In one of these studies Congress directed EPA to include:

> *"An examination of policy options that if implemented would stabilize current levels of atmospheric greenhouse gas concentrations. This study should address the need for and implications of significant changes in energy policy, including energy efficiency and development of alternatives to fossil fuels; reductions in the use of CFCs; ways to reduce other greenhouse gases such as methane and nitrous oxide; as well as the potential for and effects of reducing deforestation and increasing reforestation efforts."*

These issues are the focus of this report.

This report differs from most previous studies of the climate change issue in that it is primarily a policy assessment. Although some aspects of the relevant scientific issues are reviewed, this document is not intended as a comprehensive scientific assessment. A recent review of the state of the science is contained in the U.S. Department of Energy's State of the Art series (MacCracken and Luther, 1985a, 1985b; Strain and Cure, 1985; Trabalka, 1985).

Congress also asked EPA to prepare a companion report on the health and environmental effects of climate change in the U.S., which would examine the impact of climate change on agriculture, forests, and water resources, as well as on other ecosystems and society. In response to the latter request, EPA produced its report entitled, *The Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989). That report provides insights into the ranges of possible future effects that may occur under alternative climate change scenarios, and establishes qualitative sensitivities of different environmental systems and processes to changes in climate. The report also examines potential changes in hydrology, agriculture, forestry, and infrastructure in the Southeast, Great Lakes, California, and Great Plains regions of the United States.

Goals of this Study

Congress presented EPA with a very challenging task. From a policy perspective, it is not enough to know how emissions would have to change from current levels in order to stabilize the atmosphere. Instead, policy options must be evaluated in the context of expected economic and technological development and the uncertainties that prevent us from knowing precisely how a given level of emissions will impact the rate and magnitude of climate change. It is also necessary for the scope of this study to be global and the time horizon to be more than a century, because of the long lags built into both the economic and climatic systems (we chose 1985-2100 as the time frame for the analysis). Predictions with such a scope cannot be attempted, but scenarios can be developed to explore policy options.

Based on these considerations EPA established four major goals:

- To assemble data on global trends in emissions and concentrations of all major greenhouse gases and activities that affect these gases.

- To develop an integrated analytical framework to study how different assumptions about the global economy and the climate system could influence future greenhouse gas concentrations and global temperatures.
- To identify promising technologies and practices that could limit greenhouse gas emissions.
- To identify policy options that could influence future greenhouse gas concentrations and global warming.

To achieve these goals EPA conducted an extensive literature review and data gathering process. The Agency held several informal panel meetings, and enlisted the help of leading experts in the governmental, non-governmental, and academic research communities. EPA also conducted five workshops, which were attended by over three hundred people, to gather information and ideas regarding factors affecting atmospheric composition and options related to greenhouse gas emissions from agriculture and land-use change, electric utilities, end-uses of energy, and developing countries. Experts in NASA, the Department of Energy, and the Department of Agriculture were actively engaged.

Report Format

The structure of this report is designed to answer the following questions in turn: What is the greenhouse effect? What evidence is there that the greenhouse effect is increasing? How will the Earth's climate respond to changes in greenhouse gas concentrations? What activities are responsible for the greenhouse gas emissions? How might emissions and climate change in the future? What

TERMINOLOGY OF CLIMATE CHANGE

An attempt has been made throughout this report to avoid technical jargon, yet some specialized terminology is inevitable. The specialized terms used in this Report are defined below.

Climate System

The interactive components of our planet which determine the climate. This includes the atmosphere, oceans, land surface, sea ice, snow, glaciers, and the biosphere. Climate change can be measured in terms of any part of the system, but it is most convenient to use surface air temperature as a measure of climate, since it is the parameter for which we have the best record and it is most directly relevant to the component of the biosphere that we know best -- humans.

Radiative Forcing (also called "external forcing," "forcing," or "perturbation")

A change imposed on the climate system (as opposed to generated by the internal dynamics of the climate system) that modifies the radiative balance of the climate system. Examples include: changes in the output of the sun or the orbit of the Earth about the sun, increased concentrations of particles in the atmosphere due to volcanoes or human activity, and increased concentrations of greenhouse gases in the atmosphere due to human activity. Radiative forcing is often specified as the net change in energy flux at the tropopause (W/m^2) or the equilibrium change in surface temperature in the absence of feedbacks (°C).

Climate Feedbacks

Processes that alter the response of the climate system to radiative forcings. We distinguish between physical climate feedbacks and biogeochemical climate feedbacks. Physical climate feedbacks are processes of the atmosphere, ocean, and land surface, such as increases in water vapor, changes in cloudiness, and decreases in land- and sea-ice accompanying global warming. Biogeochemical feedbacks involve changes in global biology and chemistry, such as the effect of changes in ocean circulation on carbon dioxide concentrations and changes in albedo from shifts in ecosystems. The impact of climate feedbacks is generally measured in terms of their effect on climate sensitivity. Positive feedbacks increase climate sensitivity, while negative feedbacks reduce it.

Climate Sensitivity (or equilibrium sensitivity)

The ultimate change in climate that can be expected from a given radiative forcing. Climate sensitivity is generally measured as the change in global average surface air temperature when equilibrium between incoming and outgoing radiation is reestablished following a change in radiative forcing. A common benchmark, which we use in this report, is the equilibrium temperature increase associated with a doubling of the concentration of carbon dioxide from preindustrial levels. The National Academy of Sciences has estimated that this sensitivity is in the range of 1.5-4.5°C, with a recent analysis suggesting 1.5-5.5°C; a reasonable central uncertainty range is 2-4°C.

TERMINOLOGY OF CLIMATE CHANGE
(continued)

Transient Response

The time-dependent response of climate to radiative forcing. Climate responds gradually to changes in radiative forcing, primarily because of the heat capacity of the oceans. The transient mode is characterized by an imbalance between incoming and outgoing radiation. Given the changing concentrations of greenhouse gases the Earth's climate will be in a transient mode for the foreseeable future. Most GCMs (see below), however, have so far examined equilibrium conditions because transient effects are much more difficult to analyze.

Albedo

The fraction of incoming solar radiation that is reflected back into space.

Flux

Flow per unit time per unit area. The flow can be of energy (e.g., watts per square meter $[W/m^2]$) or mass (e.g., grams per square meter per day $[g\ m^{-2}d^{-1}]$).

General Circulation Model (GCM)

A computer model of the Earth's climate based on equations that describe, among other things, the conservation of energy, momentum, and mass, and which explicitly calculates the distribution of wind, temperature, precipitation and other climatic variables. Such models are applied to the atmosphere, to the oceans, or to both coupled together.

Solar Luminosity, Solar Constant

Solar luminosity is the total amount of energy emitted by the sun. The so-called "solar constant" is the average amount of energy received at the top of the Earth's atmosphere at the mean Earth-sun distance; this amount varies with changes in solar luminosity.

Troposphere, Tropopause, Stratosphere

The troposphere is the lower atmosphere, from the ground to an altitude of about 8 kilometers (km) at the poles, 12 km in midlatitudes and 18 km in the tropics. The tropopause marks the top of the troposphere; temperature decreases with altitude below the tropopause and increases with altitude above the tropopause to the top of the stratosphere. The stratosphere extends from the tropopause to about 50 km. The troposphere and stratosphere together contain more than 99.9% of the mass of the atmosphere.

technologies are available for limiting greenhouse gas emissions? And what domestic and international policy options, if implemented, would help to stabilize global climate?

This chapter provides a general introduction to the climate change issue and reviews selected previous studies. Chapter II discusses the greenhouse gases, their sources and sinks, chemical properties, current atmospheric concentrations and distributions, and related uncertainties. Chapter III relates the greenhouse gases to the process of climatic change. Once this link is made, Chapter IV examines those human activities that affect trace-gas emissions and ultimately influence climate change. Chapter V discusses the scenarios developed for this report to assist us in thinking about possible future emissions and climate change. Chapter VI then presents sensitivity analyses of the modeling results. Chapter VII gives a detailed description of existing and emerging technologies that should be considered in the formulation of a comprehensive strategy for mitigating global warming. Chapter VIII outlines domestic policy options, and the concluding chapter (Chapter IX) discusses international mechanisms for responding to climate change.

THE GREENHOUSE GASES

Congress presented EPA with an extremely challenging task. Once emitted, greenhouse gases remain in the atmosphere for decades to centuries. As a result, if emissions remained constant at 1985 levels, the greenhouse effect would continue to intensify for more than a century. Carbon dioxide concentrations would reach 440-500 parts per million (ppm) by 2100, compared with about 350 ppm today, and about 290 ppm 100 years ago. CFC concentrations would increase by more than a factor of three from current levels, while nitrous oxide concentrations would increase by about 20%, and methane concentrations might remain roughly constant. Indeed, in many cases drastic cuts in emissions would be required to stabilize atmospheric composition.

Carbon dioxide

Carbon dioxide (CO_2) is the most abundant and single most important greenhouse gas in the atmosphere. Its concentration has increased by about 25% since the industrial revolution. Detailed measurements since 1958 show an increase from 315 to 350 parts per million (ppm) by volume (Figure 1-1). These data clearly demonstrate that human activities are now of such a magnitude as to produce global consequences. Current emissions are estimated at 5.5 billion tons of carbon (Pg C) from fossil-fuel combustion and 0.4-2.6 Pg C from deforestation.[1] Most of this CO_2 remains in the atmosphere or is absorbed by the ocean. Even though only about half of current emissions remain in the atmosphere, currently available models of CO_2 uptake by the ocean suggest that substantially more than a 50% cut in emissions is required to stabilize concentrations at current levels (Figure 1-2).

Methane

The concentration of methane (CH_4) has more than doubled during the last three centuries. Methane, which is currently increasing at a rate of 1% per year, is responsible for about 20% of current increases in the greenhouse effect. Of the major greenhouse gases, only CH_4 concentrations can be stabilized with modest cuts in anthropogenic emissions: a 10-20% cut would suffice to stabilize concentrations at current levels due to methane's relatively short atmospheric lifetime (assuming that the lifetime remains constant, which may require that hydrocarbon and carbon monoxide emissions be stabilized).

---

[1] One billion tons of carbon = 10^{15} grams of carbon = 1 petagram of carbon (Pg C).

FIGURE 1-1

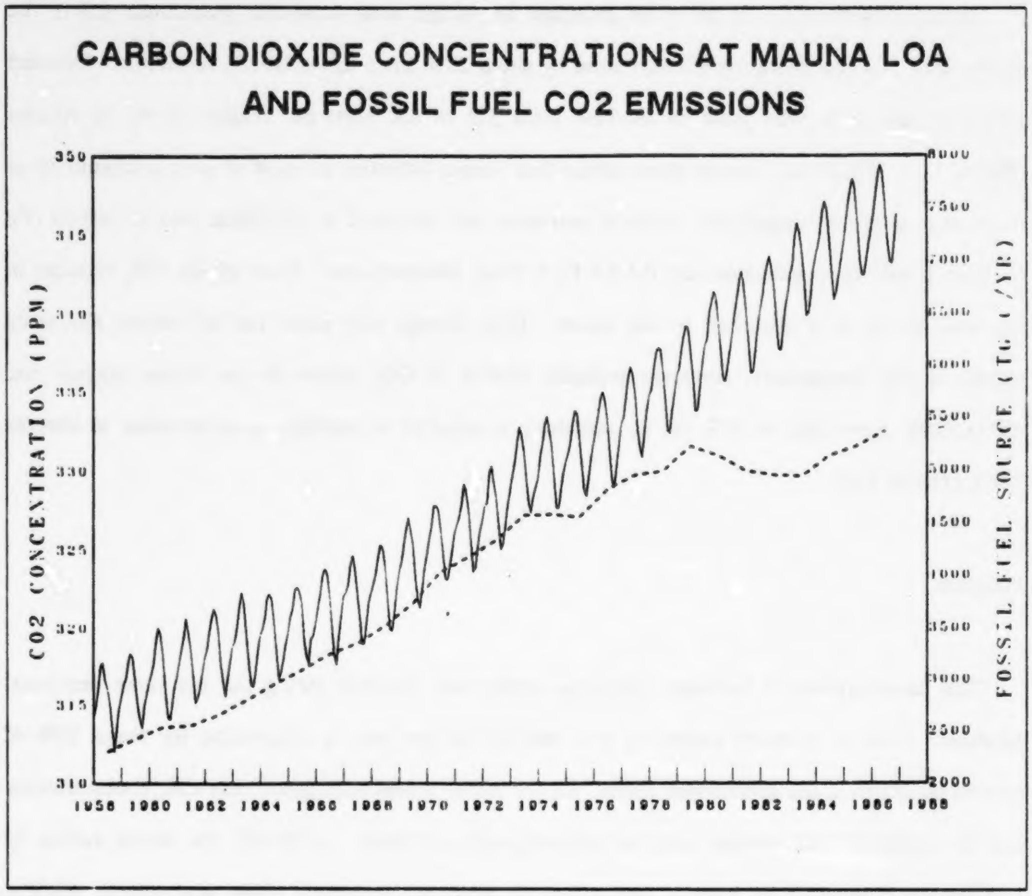

Figure 1-1. The solid line depicts monthly concentrations of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. The steadily increasing concentration of atmospheric CO_2 at Mauna Loa since the 1950s is caused primarily by the CO_2 inputs from fossil fuel combustion (dashed line). Note that CO_2 concentrations have continued to increase since 1979, despite relatively constant emissions; this is because emissions have remained substantially larger than net removal, which is primarily by ocean uptake. (Sources: Keeling, 1983, pers. communication; Komhyr et al., 1985; NOAA, 1987; Conway et al., 1988; Rotty, 1987, pers. communication.)

FIGURE 1-2

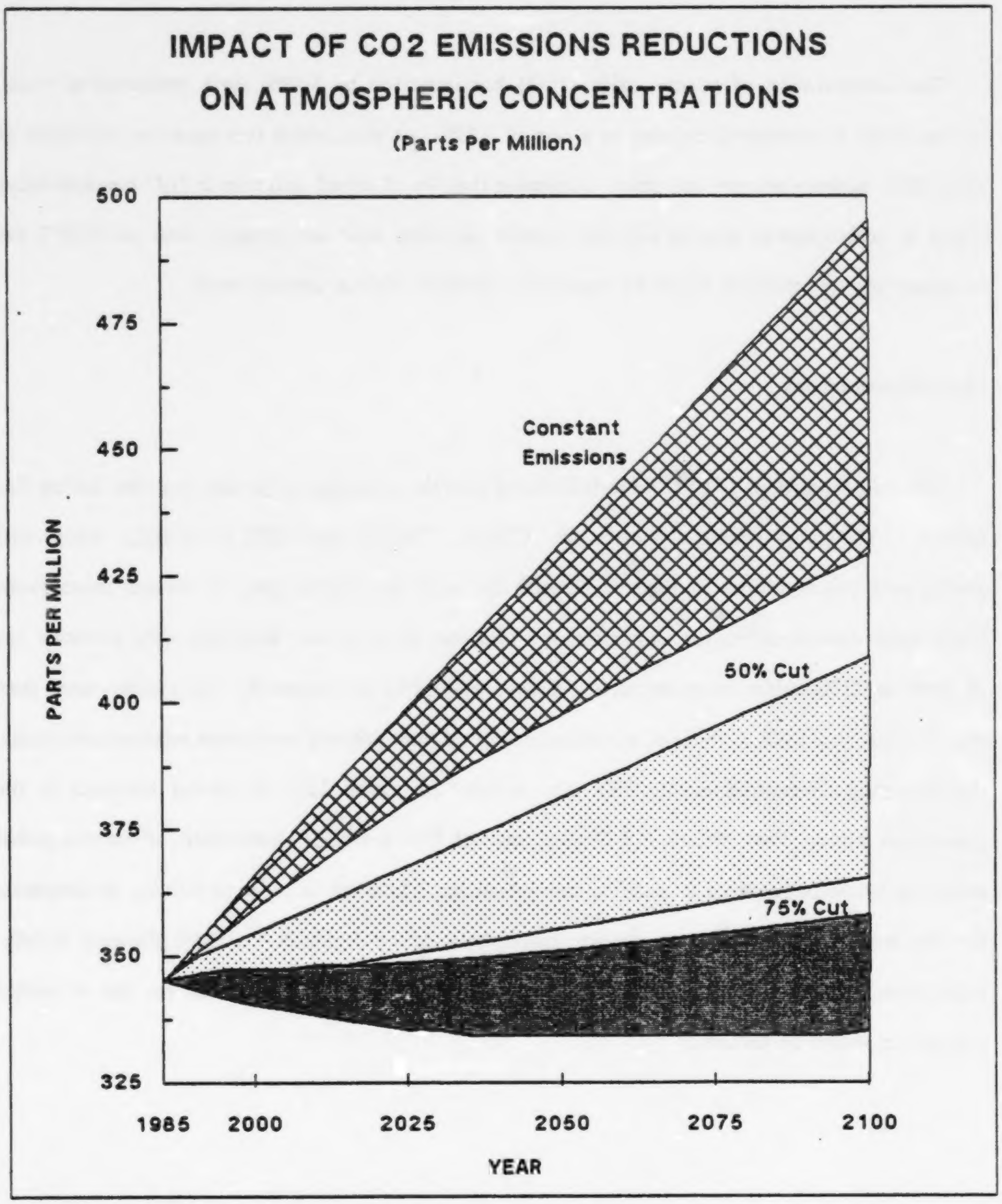

Figure 1-2. The response of atmospheric CO_2 concentrations to arbitrary emissions scenarios based on two one-dimensional models of ocean CO_2 uptake. See Chapter VI for a description and models. (Sources: Hansen et al., 1984; Lashof, 1988; Siegenthaler, 1983).

Nitrous oxide

The concentration of nitrous oxide (N_2O) has increased by 5-10% since preindustrial times. Nitrous oxide is currently increasing at a rate of 0.25% per year, which represents an imbalance of about 30% between sources and sinks. Assuming that the observed increase in N_2O concentrations is due to anthropogenic sources and that natural emissions have not changed, then an 80-85% cut in anthropogenic emissions would be required to stabilize N_2O at current levels.

Chlorofluorocarbons

Chlorofluorocarbons (CFCs) were introduced into the atmosphere for the first time during this century. The most common species are CFC-12 (CF_2Cl_2) and CFC-11 ($CFCl_3$), which had atmospheric concentrations in 1986 of 392 and 226 parts per trillion (ppt) by volume, respectively. While these concentrations are tiny compared with that of CO_2, each additional CFC molecule has as much as 20,000 times more impact on climate, and CFCs are increasing very rapidly--more than 4% per year since 1978. A focus of attention because of their potential to deplete stratospheric ozone, the increasing concentrations of CFCs also account for about 15% of current increases in the greenhouse effect. For CFC-11 and CFC-12, cuts of 75% and 85%, respectively, of current global emissions would be required to stabilize concentrations. However, in order to stabilize stratospheric chlorine levels -- of particular concern for stratospheric ozone depletion -- a 100% phaseout of fully-halogenated compounds (those that do not contain hydrogen) and a freeze on the use of methyl chloroform would be required.

Other gases influencing composition

Emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and other species, in addition to the greenhouse gases just described, are also changing the chemistry of the atmosphere. This change in atmospheric chemistry alters the distribution of ozone and the oxidizing power of the atmosphere, changing the atmospheric lifetimes of the greenhouse gases. If the concentrations of the long-lived gases were stabilized, it might only be necessary to freeze emissions of the short-lived gases at current levels to stabilize atmospheric composition.

PREVIOUS STUDIES

Evidence that the composition of the atmosphere is changing has led to a series of studies analyzing the potential magnitude of future greenhouse gas emissions. A few of these studies have carried the analysis further, making projections of the timing and severity of future global warming. The first generation of these studies focussed principally on energy use and CO_2 emissions. (See, for example, Arrhennius, 1896; NAS, 1979; Clark et al., 1982; IIASA, 1983; Nordhaus and Yohe, 1983; Rose et al., 1983; Seidel and Keyes, 1983; Edmonds and Reilly, 1983b, 1984; Legasov, et al. 1984; Goldemberg et al., 1985, 1987; and Keepin et al., 1986). Subsequent studies have recognized that other radiatively-active trace gases significantly amplify the effects of CO_2. (See, for example, Lacis et al., 1981; Ramanathan et al., 1985; Dickinson and Cicerone, 1986; WMO, 1985; and Mintzer, 1987). In the following sections, some of the most important of these earlier analyses are reviewed in order to provide a basis for comparison with this study.

Estimates of the Climatic Effects of Greenhouse Gas Buildup

The first serious analysis of the effect of increasing CO_2 concentrations on global warming was conducted by the Swedish chemist Svante Arrhennius (1896). Arrhennius, concerned about the rapidly increasing rate of fossil-fuel use in Europe, recognized that the resulting increase in the atmospheric concentration of CO_2 would alter the thermal balance of the atmosphere. Using a simplified, one-dimensional model, Arrhennius estimated that if the atmospheric concentration of CO_2 doubled, the surface of the planet would warm by about 5°C. (The expected equilibrium climate change associated with a doubling of CO_2 has become a benchmark. That is, many studies examine the consequences of greenhouse gas increases with a total warming effect equivalent to that from a doubling of the concentration of CO_2.)

In 1979, a study by the U.S. National Academy of Sciences (NAS) evaluated the impact on global climate of doubling the concentration of CO_2 relative to the preindustrial atmosphere (NAS, 1979). The NAS study concluded that the planet's surface would be 1.5-4.5°C warmer under such conditions. Subsequent re-evaluations by NAS (1983, 1987) as well as the "State-of-the-Art" report issued by the Department of Energy (MacCracken and Luther, 1985a) have reaffirmed this estimate.

Recent work by Dickinson (1986) suggests that the effects of a greenhouse gas buildup radiatively equivalent to doubling the preindustrial concentration of CO_2 might warm the planet to a greater extent than had previously been expected. Focusing on the uncertainties in current understanding of atmospheric feedback processes, Dickinson estimated that the warming effect of such a buildup was likely to be between 1.5° and 5.5°C. Dickinson's "best guess" was that the actual equilibrium warming would be between 2.5° and 4.5°C.

Studies of Future CO_2 Emissions

For the next eighty years after Arrhennius issued his warning, little additional scientific attention was directed toward understanding the factors that contribute to future greenhouse gas emissions. By the mid-1970s, measurements of atmospheric CO_2 concentrations at Mauna Loa begun by Keeling during the International Geophysical Year (1957-1958) provided indisputable evidence of a long-term increasing trend (see Figure 1-2), while the oil embargo of 1973 and the nuclear power debate focussed attention on future energy supplies. Increasing interest was placed on the problems of projecting future global energy use and on estimating the resulting CO_2 emissions.

A major international study of future energy use was conducted by the International Institute for Applied Systems Analysis (IIASA, 1981 and 1983). Employing an international group of almost 200 scientists, the IIASA team developed a set of computer models to estimate regional economic growth, energy demand, energy supply, and future CO_2 emissions. Although the models were never completely integrated, the first phase of the IIASA study produced two complete scenarios of global energy use. The IIASA low scenario generated CO_2 emissions of about 10 petagrams of carbon per year (Pg C/yr) in 2030. The IIASA high scenario projected emissions of about 17 Pg C/yr in 2030. In the second phase of the IIASA study a third scenario was outlined, emphasizing increased use of natural gas. In this third scenario, CO_2 emissions in 2030 were only about 9.4 Pg C/yr.

In 1983 Edmonds and Reilly, two U.S. economists, developed a detailed partial equilibrium model to investigate the effects of alternative energy policies and their implications for future CO_2 emissions (Edmonds and Reilly, 1983a). This model disaggregates the world into nine geopolitical regions. It offers a highly detailed picture of the supply side of the world's commercial energy business but only limited detail on the demand side. It considers nine primary and four secondary forms of commercial energy (including biomass grown on plantations) but ignores non-commercial uses of biomass for fuel. Using explicit assumptions about regional population changes and economic growth and combining them with assumptions about technological change and the costs of extracting various grades of fuel resources in each region, the model calculates supply and demand schedules for each type of fuel.

For their first major report, Edmonds and Reilly (1983b) developed a Base Case energy future for the period 1975 to 2050. In this scenario, CO_2 emissions in 2050 were approximately 26.3 Pg C/yr. The authors generated several other scenarios in this study that reflected the effect of various taxes imposed on fuel supply and use. These taxes reduced CO_2 emissions by varying amounts, with emissions in some scenarios falling as low as 15.7 Pg C/yr in 2050. In 1984 Edmonds and Reilly produced a new set of scenarios for the U.S. Department of Energy by varying other key parameters in the model (Edmonds and Reilly, 1984). In these new scenarios, CO_2 emissions in 2050 vary from about 7 to 47 Pg C/yr, with a new "Base Case" value of about 15 Pg C/yr. The principal force contributing to the difference between the results of the two studies conducted by Edmonds and Reilly is the higher coal price applied in the second study.

A number of other studies have used the Edmonds-Reilly (ER) model to project future energy use and CO_2 emissions. The most important of these were studies conducted by the U.S. Environmental Protection Agency (Seidel and Keyes, 1983) and Rose et al. (1983). The EPA study used the ER model to generate 13 scenarios for the period 1975-2100, which were used as a basis for investigating whether actions taken now to reduce fossil-fuel consumption could significantly delay a future global warming. Six baseline and seven policy-driven scenarios were investigated in this study. The scenarios generated in the EPA study projected CO_2 emissions in 2050 at levels of 10-18 Pg C/yr. The authors concluded from these scenarios that the timing of a 2°C warming is not very sensitive to the effects of the energy policies they tested.

Rose and his colleagues at the Massachusetts Institute of Technology (MIT) also used the ER model to study the effect of various energy policy options on the timing and extent of future CO_2 emissions (Rose et al., 1983). Eleven scenarios were investigated, covering the period from 1975 to 2050 and incorporating a much wider range of assumptions and policies than those tested in the EPA study. Rose et al. studied the effects of increased energy efficiency, increased fossil-fuel prices, higher nuclear energy supply costs and a moratorium on building nuclear plants, lower photovoltaic costs, higher oil prices, and a cutoff of oil imports from the Middle East. The MIT study went beyond the ER model results to provide detailed estimates of the materials required for construction and operation of energy facilities in each scenario. In the MIT scenarios, emissions of CO_2 in 2050 ranged from less than 3 to about 15 Pg C/yr. The most important new conclusion of Rose et al. was that a feasible "option space exists in which the CO_2/climate problem is much ameliorated" through energy policy choices and improvements in technology.

In 1983 the National Academy of Sciences completed a Congressionally-mandated study to evaluate, among other things, the effects of fossil-fuel development activities authorized by the Energy Security Act of 1980 (NAS, 1983). One of the chapters in this study, authored by energy economists Nordhaus and Yohe, used a compact model of global economic growth and energy use to analyze CO_2 emissions between 1975 and 2100 (Nordhaus and Yohe, 1983). Unlike the partial equilibrium approach employed in the ER model, the Nordhaus and Yohe (NY) model used a generalized Cobb-Douglas production function to estimate future energy demand. In this approach global GNP is estimated as a function of assumptions about average rates of change in labor productivity, population, and energy consumption. Demand for energy is separated into two categories, fossil and non-fossil. Projections of CO_2 emissions (based on the weighted average release rate from fossil fuels) were used as inputs to a simple airborne fraction model of the carbon cycle.

The NY analysis used an approach called "probabilistic scenario analysis," to evaluate the effects on CO_2 emissions of alternative assumptions used in the model. The results of 1000 cases were examined. The CO_2 emissions trajectories in these cases were presented as percentiles in the overall distribution among the 1000 scenarios. Using this approach to uncertainty analysis, Nordhaus and Yohe concluded that the 50th percentile for carbon emissions in 2050 was approximately 15 Pg C/yr. The 95th percentile case suggested that emissions in 2050 would likely be less than 26 Pg C/yr, while the 5th percentile case indicated that emissions would likely be greater than 5 Pg C/yr.

The probabilistic approach was subsequently applied to the more detailed ER model using Monte Carlo analysis (Edmonds et al., 1986; Reilly et al., 1987). The results of this analysis suggest a larger total range of uncertainty and a substantially lower median emissions estimate compared with the Nordhaus and Yohe (1983) results. When the likely correlations between model parameters are taken into account Edmonds et al. obtain emissions of 7.7 Pg C/yr in 2050 for the 50th percentile case with 5th and 95th percentile bounds of 2.3 and 58.1 Pg C/yr, respectively. Note that the median result is about half of the Base Case scenario obtained in earlier analysis by Edmonds and Reilly (1984).

In 1984 Legasov et al. published one of a continuing series of Soviet analyses of future global energy use and its environmental implications. Legasov et al. analyzed two scenarios in which energy demand reaches 6 and 20 kilowatts per capita by the end of the next century. Annual per capita energy consumption is treated as a logistic function, approaching these levels asymptotically in 2100. Assuming a global population of 10 billion persons, the minimal variant implies a global energy demand of 60 terawatts (TW), about six times the current level by 2100.[2] CO_2 emissions in this scenario follow a bell-shaped trajectory, peaking at about 13.3 Pg C/yr in 2050.

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[2] 1 terawatt = 10^{12} watts = 31.5×10^{18} joules per year = 31.5 exajoules (EJ) per year = 29.9 Quadrillion British Thermal Units (Quads) per year.

Goldemberg and his colleagues have used a completely different approach to projecting future energy use and its consequences for CO_2 emissions (Goldemberg et al., 1985, 1987, 1988). The Goldemberg et al. analysis is based on an end-use oriented approach to evaluating the demand for energy services, rather than the availability of energy supply. Based on detailed studies of energy demand in four countries (U.S., Sweden, India, and Brazil), Goldemberg and his colleagues developed a scenario of future energy requirements in both industrialized and developing countries. Although the study does not represent a forecast of future energy demand, it provides an "existence proof," demonstrating the feasibility of a world economy that continues to grow while consuming much less energy than it would if historical trends continue.

Emphasizing the potential to improve the efficiency of energy supply and use, per capita energy demand in the industrialized countries is cut by 50% in the Goldemberg et al. scenarios. During the same 40-year period, per capita demand for energy in the developing countries grows by about 10%, with commercial fuels displacing traditional biomass fuels at a rapid and increasing rate. Global energy demand remains essentially constant in the base case with CO_2 emissions in 2020 of 5.9 Pg C/yr, only about 5% higher than today's level.

A limitation of the Goldemberg et al. studies is that the impact of market imperfections and the rate of capital stock turnover are not fully addressed. Nonetheless, these studies, along with the Rose et al. analysis, demonstrate that economic growth can be decoupled from increases in CO_2 emissions. Experience over the last 15 years in the U.S., Western Europe, and Japan suggests that this conclusion is correct.

A study by Keepin et al. (1986) reviewed and re-evaluated the range of previous energy and CO_2 projections, including those summarized here. It concluded that the feasible range for future energy in 2050 was somewhere between about 10 and 35 TW, with CO_2 emissions between 2 and 20 Pg C/yr.

Studies of the Combined Effects of Greenhouse Gas Buildup

In the last few years a number of analysts have investigated the *combined* effects on global surface temperature of a buildup of CO_2 and other trace gases. Preliminary analysis of the impact of concentration increases during the 1970s was presented by Lacis et al. (1981) and estimates of future impacts were included in Seidel and Keyes (1983). A seminal article by Ramanathan et al. (1985) focused attention on the subject. This study used a one-dimensional radiative-convective model to estimate the impact of a continuation of current trends in the buildup of more than two dozen radiatively active trace gases between 1980 and 2030. Ramanathan and his colleagues calculated an expected value for the equilibrium warming of about 1.5°C over this period, with a little less than half of that amount due to the buildup of CO_2 alone. (The Ramanathan et al. analysis included the effects of water-vapor feedback, but not the other known feedback mechanisms; see Chapter III.) The most important conclusion of the analysis by Ramanathan et al. is that, if current trends continue and uncertainties in the future emissions projections are accounted for, the warming effects of the non-CO_2 trace gases will amplify the warming due to the buildup of CO_2 alone by a factor of between 1.5 and 3.

In 1986, Dickinson and Cicerone extended the work of Ramanathan et al. to evaluate a range of trace-gas scenarios covering the period from 1985 to 2050. Using the radiative-convective model developed by Ramanathan et al., and considering a range of emissions growth rates for the most important greenhouse gases, Dickinson and Cicerone (1986) estimated that equilibrium global average surface temperatures would rise at least 1°C and possibly more than 5°C by 2050, when the full range of atmospheric feedback processes was considered.

Each of the analyses described above was based on the assumption that historical trends in the growth of greenhouse gas emissions continue for the next 40-50 years. Mintzer (1987) has developed a model to consider the alternative: that policy and investment choices made in the next several decades will substantially alter the growth rates of future emissions. Mintzer's analysis uses a composite tool called the Model of Warming Commitment to link future rates of economic growth to the increasing atmospheric concentrations of carbon dioxide, nitrous oxide, chlorofluorocarbons, methane, and tropospheric ozone. The results are reported as the date of atmospheric commitment to a warming equivalent to doubling preindustrial CO_2 concentrations and as the magnitude of warming commitment in 2075.

Mintzer's initial analysis considered four policy-driven global scenarios, including a Base Case representing a continuation of current trends. All four scenarios support a global population of about 10 billion people and the same levels of regional economic growth. Most recent analyses, including the ones cited above and Mintzer's Base Case, indicate that a continuation of current trends would lead to a warming commitment equivalent to doubling the preindustrial concentration of CO_2 by about 2030. In Mintzer's Base Case, by 2075, the planet is committed to an eventual warming of about 3-9°C. Alternatively, in the High Emissions case, policies that increase coal use, spur deforestation, extend the use of the most dangerous CFCs and limit improvements in energy efficiency, will accelerate the onset of the "doubled CO_2 equivalent" atmosphere to about 2010 and commit the planet to a warming of about 5-15°C in 2075. By contrast, in Mintzer's Slow Buildup scenario, a warming associated with the doubled CO_2 equivalent atmosphere is postponed beyond the end of the simulation period in 2075. In the Slow Buildup scenario this level of risk reduction is achieved by aggressively pursuing policies to increase energy efficiency, limit tropical deforestation, reduce the use of the most dangerous CFCs, and shift the fuel mix from carbon-intensive fuels like coal to hydrogen-intensive fuels like natural gas, and ultimately, to energy sources that emit no CO_2.

More recently, Rotmans et al. (1988) have used a framework similar to the Model of Warming Commitment to develop scenarios of greenhouse warming based on alternative policy assumptions. Also, Rotmans and Eggink (1988) have analyzed the role of methane in greenhouse warming.

Major Uncertainties

Major uncertainties underlie many aspects of our understanding of the climate change problem. These uncertainties encompass our understanding of the geophysical processes underlying the sensitivity of the climate to perturbations, that is, the processes that control how fast greenhouse gases flow into and out of the atmosphere and biosphere, including feedback processes that may affect future concentrations of greenhouse gases, and socio-economic uncertainties that are inherent in any energy/economic model used to forecast long-term emissions. The physical uncertainties include uptake of heat and CO_2 by the ocean and any other sinks, geophysical and biogeochemical feedback mechanisms, and natural rates of emission of the greenhouse gases. The social and economic uncertainties include population growth, GNP growth, structural changes in economic systems, rates of technological change, future reliance on fossil fuels, and future compliance with the Montreal Protocol. Future rates of greenhouse gas emissions cannot be predicted with certainty. Future emissions rates will be determined by the emerging pattern of human industrial and agricultural activities as well as by the effects of feedback processes in the Earth's biogeophysical system whose details are not well understood at the present time.

All existing climate models encompass large uncertainties that limit the accuracy of the models and the level of geographic detail that can be considered. Even the best General Circulation Models (GCMs) are limited by the assumptions necessarily made about the influence of clouds, vegetation, ice and snow, soil moisture, and terrain, all of which affect the energy balance of the Earth's surface.

Two of the largest uncertainties involve our limited understanding of the role that clouds, and ocean uptake and transport of heat, play in the climate system.

Conclusions From Previous Studies

Despite the significant uncertainties that underlie our understanding of climate change, several important conclusions emerge from the existing literature. First, emissions of a number of other trace gases will amplify the future warming effect of any further buildup in the atmospheric concentration of CO_2. Second, it is too late to prevent all future global warming. Trace gases released over the last century have already committed the planet to an ultimate warming (of up to 2°C) that may be greater than any other in the period of written human history. Finally, policy choices and investment decisions made during the next decade that are designed to increase the efficiency of energy use and shift the fuel mix away from fossil fuels could slow the rate of buildup sufficiently to avoid the most catastrophic potential impacts of rapid climate change. Alternatively, decisions to rapidly expand the use of coal, extend the use of the most dangerous CFCs, and rapidly destroy the remaining tropical forests could "push up the calendar," accelerating the onset of a dangerous global warming.

The rate at which climate may change must be of particular concern to policy makers. The temperature increases resulting from doubling the concentration of CO_2 that are predicted by most GCMs are comparable to the increase that has occurred since the last ice age. The difference is that the period of time within which this increase could happen is much shorter. Atmospheric scientists predict that within approximately 100 years we could experience temperature increases equivalent to those that have occurred over the past 18,000 years (about 5°C; see Chapter III). It is not clear that our ecosystems and economic systems will be able to adjust to such a rapid change in global mean temperatures. Increases in world population, coupled with limited environmental and agricultural resources, increase the vulnerability of social systems to climatic change.

The potential impacts of climatic change are highly uncertain and are beyond the scope of this report. They are addressed in the companion volume, *The Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989). The findings of this study collectively suggest that the climatic changes associated with a global warming of roughly 2-4°C would result in "a world that is different from the world that exists today. Global climate change will have significant implications for natural ecosystems; for when, where, and how we farm; for the availability of water to drink and water to run our factories; for how we live in our cities; for the wetlands that spawn our fish; for the beaches we use for recreation; and for all levels of government and industry." Although sensitivities were identified in this report, detailed regional predictions of climate change cannot be made at this time. Thus potential responses to the greenhouse gas buildup must be viewed in the context of risk management, or buying insurance.

A second major concern is that the greenhouse gases have very long lifetimes once they are introduced into the atmosphere. Although there is a substantial lag between the time when a greenhouse gas is introduced into the atmosphere and when its full impact on climate is realized, once the gases are in the atmosphere they will remain there for a long time. The longer the delay before mitigating action is taken, the larger will be the commitment to further global warming.

Policy makers must determine how best to minimize the costs of global warming to the peoples of the world and the damage to ecosystems. But global warming is a complex problem for which there is no single, simple solution. No single policy initiative will completely mitigate man-made climate change. The sources, sectors, and countries contributing to the emissions of greenhouse gases are numerous (Chapter IV).

Compounding the difficulty of identifying solutions to the greenhouse problem is that the greenhouse gases do not all have the same forcing effect on global temperatures. In fact, CO_2 is the least effective absorbent of infrared radiation of all of the greenhouse gases per additional molecule added to the atmosphere. Because the combined effect of the other greenhouse gases is comparable to the effect of CO_2, mitigatory policies cannot be directed solely at reducing CO_2 emissions. The sources of methane, CFCs, nitrous oxide, and other gases must therefore be carefully considered.

As we explore the options for limiting greenhouse gas emissions in this report, it is important to remember two salient points: (1) Global warming is an international problem whose solution will require extensive cooperation between both industrialized and developing countries; and (2) No single economic sector can be held entirely responsible for the greenhouse effect. In focusing on strategies to stabilize climate in this Report, we recognize that the optimal mix of adaptation and prevention is uncertain. The Earth is already committed to some degree of climatic change, so adaptation to some level of change is essential. On the other hand, the highest rates of potential change may be considered unacceptable, requiring some degree of prevention. Stabilizing strategies would require global cooperation of an unprecedented nature and could be costly for some countries. The activities responsible for greenhouse gas emissions are economically valuable, the distribution of emissions is large, and the responsible countries reflect diverse economies and a variety of interests. Adaptation strategies, on the other hand, can be adopted unilaterally. They may also be less burdensome because the costs will be spread out into the future when countries may be better able to afford them. Imposing climatic change on our grandchildren, however, raises serious concerns regarding intergenerational equity.

CURRENT NATIONAL AND INTERNATIONAL ACTIVITIES

Subsequent to the Congressional request to produce this report and the companion document on potential effects of climate change there have been a wide variety of new domestic and international initiatives related to climatic change.

National Research and Policy Activities

The Global Climate Protection Act of 1987 requires that:

> *The President, through the Environmental Protection Agency, shall be responsible for developing and proposing to Congress a coordinated national policy on global climate change.*

This Act is a very broad mandate that will require close cooperation between EPA and other agencies (including NASA, NOAA, the Corps of Engineers, and the Departments of Energy, Agriculture, and the Interior, the National Climate Program Office, and the Domestic Policy Council).

The Global Climate Protection Act also requires that the Secretary of State and the EPA Administrator jointly submit, by the end of 1989, a report analyzing current international scientific understanding of the greenhouse effect, assessing U.S. efforts to gain international cooperation in limiting global climate change, and describing the U.S. strategy for seeking further international cooperation to limit global climate change. This report, along with those being developed by other Federal agencies, will provide a foundation upon which a national policy can be formulated.

International Activities

The greenhouse gas problem is an international issue. In order to respond effectively to this problem, the nations of the world must act in concert. Several international organizations have recognized the need for multilateral cooperation and have become involved with the global climate change issue. The United Nations Environment Programme (UNEP) is responsible for conducting climate impact assessments. The World Meteorological Organization (WMO) is supporting research on and monitoring of atmospheric and physical sciences. The International Council of Scientific Unions (ICSU) is developing an international geosphere-biosphere program.

The U.S. Government is supporting the Intergovernmental Panel on Climate Change (IPCC) established under the auspices of UNEP and WMO. The IPCC, which held its first meeting in November 1988, will help ensure an orderly international effort in responding to the threat of global climate change. At its first meeting the IPCC established three working groups: the first, to assess the state of scientific knowledge on the issue, will be chaired by the United Kingdom; the second, to assess the potential social and economic effects from a warming, will be chaired by the Soviet Union; and the third, to examine possible response strategies, including options for limiting emissions and adapting to change, will be chaired by the United States.

In addition, several countries have held or plan to hold international conferences on global climate change. These include Canada, The Federal Republic of Germany, Italy, Japan, India, Egypt, and the Netherlands. The Netherlands and the Federal Republic of Germany (through the Enquete Commission) are undertaking analyses of policy options.

The efforts of all of these organizations may be hindered if some countries perceive themselves as winners instead of losers, as a result of climate change. For example, both Canada and the Soviet

Union, which have vast land areas that are currently largely unusable because of their severe climates, could benefit from increased agricultural productivity as those areas become warmer. But the notion that a global warming might be beneficial to some may prove fallacious. Two particular problems might limit anticipated benefits. First, if the shift in climatological zones happens too quickly, ecosystems may not be able to keep up and may be severely disrupted. Although the Canadian climate may become more conducive to certain types of forests, if the forests can't migrate fast enough and therefore die back as the climatological zones shift northward, benefits to the Canadians will be reduced. Second, although shifts towards more favorable climatic conditions may be a necessary condition for increased agricultural productivity, a warmer climate in itself may not be sufficient. For example, the northern areas of Canada might not have the proper soil composition for high agricultural yields. The conclusion must therefore be drawn that it is difficult to predict what the net costs and benefits of climate change will be for any one country.

The global warming issue is an international concern. In order to develop a responsible program, the U.S. government must consider the feasibility of achieving both domestic and international acceptance and implementation of policy initiatives. Otherwise, the effectiveness of programs instituted by any one country could be compromised by the lack of participation by other countries. International collaboration must be pursued.

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CHAPTER II

GREENHOUSE GAS TRENDS

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FINDINGS

The composition of the atmosphere is changing as the result of human activities. Increases in the concentration of carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs) are well documented. In addition, tropospheric (lower atmospheric) and stratospheric (upper atmospheric) chemistry are being modified due to the addition of these gases as well as emissions of carbon monoxide, nitrogen oxides, and other compounds. Specifically, we find that:

- The concentration of carbon dioxide in the atmosphere has increased by 25% since the industrial revolution. Detailed measurements since 1958 show an increase of about 35 parts per million by volume. Both land clearing and fossil fuel combustion have contributed to this rise, but the fossil fuel source has dominated in recent years. Carbon dioxide is increasing at a rate of about 0.4% per year and is responsible for about half of the current increases in the greenhouse effect. Carbon cycle models indicate that the oceans are responsible for the uptake of most of the fossil fuel CO_2 that does not remain in the atmosphere. The total net uptake of CO_2 by the oceans and the net uptake/release of CO_2 by the terrestrial biosphere cannot be precisely determined at this time.

- The concentration of methane has more than doubled during the last three centuries. There is considerable uncertainty about the total emissions from specific sources of methane, but the observed increase is probably due to increases in a number of sources as well as changes in tropospheric chemistry. Agricultural sources, particularly rice cultivation and animal husbandry, have probably been the most significant contributor to historical increases in concentrations. But there is the potential for rapid growth in emissions from landfills, coal seams, permafrost, natural gas exploration and pipeline leakage, and biomass burning associated with forest clearings in the future. Methane is increasing at a rate of 1% per year and is responsible for about 20% of the current increases in the greenhouse effect.

- The concentration of nitrous oxide has increased by 5-10% since preindustrial times. The cause of this increase is highly uncertain, but it appears that the use of nitrogenous fertilizer, land clearing, biomass burning, and fossil fuel combustion have all contributed. Nitrous oxide is over 200 times more powerful, on a per molecule basis, than carbon dioxide as a greenhouse gas, and can also contribute to stratospheric ozone depletion. Nitrous oxide is currently increasing at a rate of about 0.25% per year, which represents an imbalance between sources and sinks of about 30%. Nitrous oxide is responsible for about 6% of the current increases in the greenhouse effect.

- CFCs were introduced into the atmosphere for the first time during this century; the most common species are CFC-12 and CFC-11 which had atmospheric concentrations in 1985 of 380 and 220 parts per trillion by volume, respectively. While these concentrations are tiny compared with that of carbon dioxide, these compounds are about 30,000 times more powerful, on a per molecule basis, than carbon dioxide as a greenhouse gas and are increasing very rapidly -- 5% per year from 1978 to 1983. Of major concern because of their potential to deplete stratospheric ozone, the CFCs also represent about 15% of the current increases in the greenhouse effect.

- The chemistry of the atmosphere is changing due to emissions of carbon monoxide, nitrogen oxides, and volatile organic compounds, among other species, in addition to the changes in the greenhouse gases just described. This alters the amount and distribution of ozone and the oxidizing power of the atmosphere, which changes the lifetimes of methane and other greenhouse gases. Changes in global ozone are quite uncertain, and may have contributed to an increase or decrease in the warming commitment during the last decade.

INTRODUCTION

The composition of the Earth's atmosphere is changing. Detailed background atmospheric concentration measurements combined with analyses of ancient air trapped in Antarctic and Greenland ice now give a compelling picture, not only of recent trends, but also of major changes that have occurred since preindustrial times. Mounting evidence that the atmosphere is changing has increased the urgency of understanding the processes that control atmospheric composition and the significance of the changes that are taking place. In this chapter we examine what is known and not known about the gases expected to be most important in altering climate during the coming decades. For each gas, we present data regarding its concentration history and geographic distribution, its sources and sinks, and its chemical and radiative interactions in the atmosphere. This information is summarized at the end of the Chapter in Table 2-2.

The concentrations of a number of greenhouse gases have already increased substantially over preindustrial levels. The estimated relative radiative forcing from the major gases (excluding water vapor and clouds) is illustrated in Figure 2-1 for the period 1880-1980 and for the expected concentration changes during the 1980s. Carbon dioxide accounted for about two-thirds of the total forcing over the last century, but its relative importance has declined to about half the total in recent years due to more rapid growth in other gases during the last few decades (see Chapter IV). Particularly important has been the recent growth in chlorofluorocarbon (CFC) concentrations. Methane (CH_4) has remained the second most important greenhouse gas, responsible for 15-20% of the forcing. With the recent signing of the Montreal Protocol on Substances that Deplete the Ozone Layer, growth in CFC concentrations is likely to be substantially restrained compared with what has been assumed until recently (e.g., Ramanathan et al., 1985; see Chapters IV and V). The relative

FIGURE 2-1

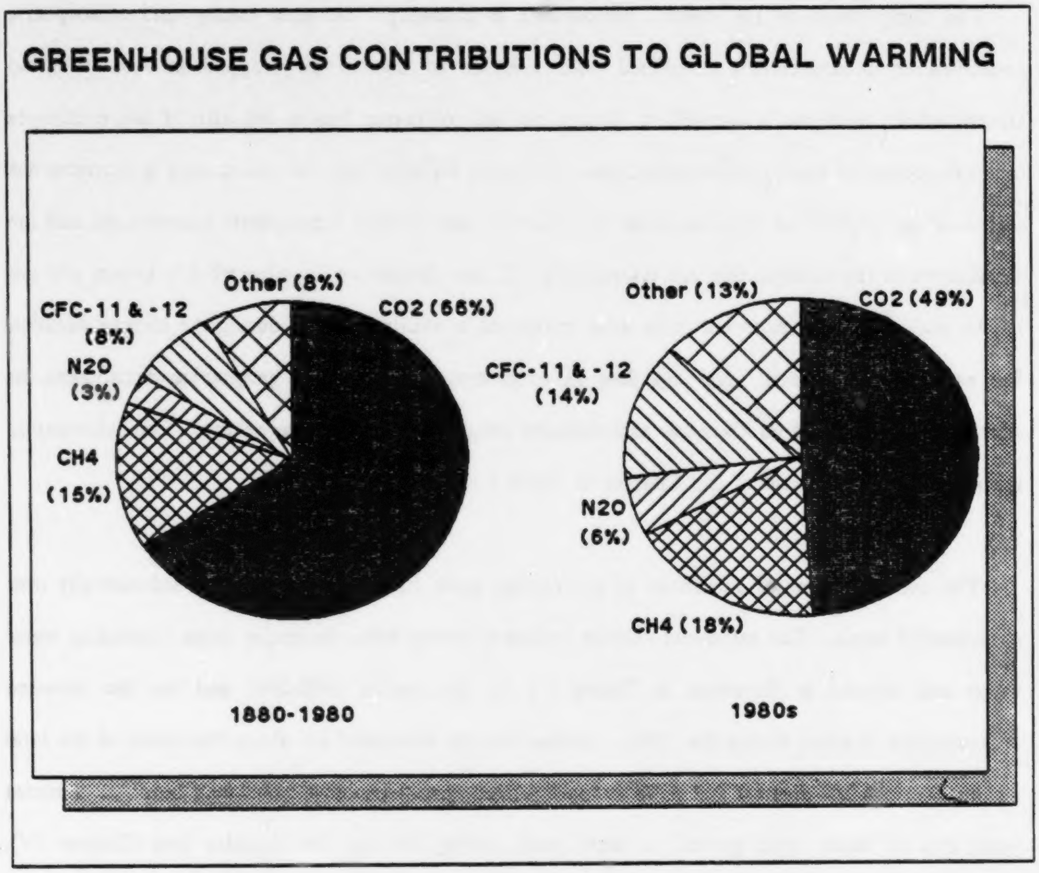

Figure 2-1. Based on estimates of the increase in concentration of each gas during the specified period. The "Other" category includes other halons, tropospheric ozone, and stratospheric water vapor. The contribution to warming of the "Other" category is highly uncertain. (Sources: 1880-1980: Ramanathan et al., 1985; 1980s: Hansen et al., 1988.)

importance of CO_2 is therefore likely to increase again in the future unless these emissions are also restricted (Chapter V).

The radiative impact of greenhouse gases is characterized here in terms of the effect of concentration changes on surface temperatures in the absence of climate feedbacks. Climate feedbacks are defined and discussed in Chapter III, where the climatic effects of changes in greenhouse gases are put into the broader context of other factors that influence climate. The human activities that are apparently responsible for the concentration trends documented in this chapter are described in Chapter IV.

CARBON DIOXIDE

Concentration History and Geographic Distribution

Carbon dioxide (CO_2) is the most abundant and single most important greenhouse gas (other than water vapor) in the atmosphere. Its role in the radiative balance, and its potential for altering the climate of the Earth have been recognized for over a hundred years. Chemical measurements of atmospheric CO_2 were made in the 19th Century at a few locations (Fraser et al., 1986a; From and Keeling, 1986). However, the modern high-precision record of CO_2 in the atmosphere did not begin until 1958, the International Geophysical Year (IGY), when C.D. Keeling of Scripps Institution of Oceanography pioneered measurements of CO_2 using an infrared gas analyzer at Mauna Loa Observatory (MLO) in Hawaii and at the South Pole. Since 1974, background measurements of atmospheric CO_2 have been made continuously at four stations (Pt. Barrow, Alaska; Mauna Loa, Hawaii; American Samoa; and the South Pole) as part of the Geophysical Monitoring for Climatic Change (GMCC) program of the National Oceanic and Atmospheric Administration (NOAA) of the

U.S. Department of Commerce. In addition to the continuous monitoring stations, NOAA/GMCC also operates a cooperative sampling network. Flask samples of air are collected weekly from these sites and are shipped to the GMCC facility in Boulder, Colorado, for analysis. The sampling network began before 1970 at a few initial sites, expanded to a network of 15 stations in 1979, and, as of 1986, consisted of ~26 stations (Komhyr et al., 1985; Conway et al., 1988). In addition to the U.S. programs, surface measurements of atmospheric CO_2 around the globe are made by many countries including Australia, Canada, France, Italy, Japan, New Zealand, West Germany, and Switzerland.

Mauna Loa

The MLO CO_2 record is shown in Figure 1-2 in Chapter I. CO_2 steadily increased from 315 parts per million by volume (ppm) in 1958 to 346 ppm in 1986. This corresponds to an increase at the rate of 0.4% per year, or a mean increase of 1.5 ± 0.2 ppm per year. From 1958 to 1986, CO_2 at Mauna Loa increased by 31 ppm; over the same period, fossil fuel combustion (shown also in Figure 1-2) was a source of 117 petagrams (Pg)[1] of carbon (C) as CO_2 to the atmosphere, which is equivalent to 56 ppm of CO_2. The apparent fraction of the fossil fuel sources of CO_2 that remained in the atmosphere during this period is thus 55%. As other net sources of CO_2, particularly deforestation (see below), may have been important during this period, the actual fraction of anthropogenic carbon emissions remaining in the atmosphere is uncertain. Superimposed on the increasing secular trend of atmospheric CO_2 are regular seasonal oscillations: the concentration peaks in May/June, decreases steadily through the summer, and reaches a minimum in September/October. The seasonal peak-to-trough amplitude is ~5.8 ppm. The seasonal cycle of CO_2 at Mauna Loa and at other northern hemispheric locations is caused primarily by the natural dynamics of the terrestrial biosphere: There is net removal of CO_2 from the atmosphere via photosynthesis during the growing season, and net return of CO_2 to the atmosphere via respiration and decomposition processes during the rest of the year.

---

[1] peta = 10^{15}, giga = 10^9, 1 ton = 10^6 grams. Thus, 1 petagram (Pg) = 1 gigaton (Gt).

Despite its regular appearance, there are interannual variations in the CO_2 concentration measured at MLO. Annual mean concentration changes do not remain uniform throughout the duration of the record, but have large fluctuations around the mean (Keeling, 1983). These excursions of atmospheric CO_2 from the mean generally occur during El Niño-Southern Oscillation events, where the large-scale perturbations of atmospheric temperature, precipitation, and other circulation statistics also alter the biological, chemical, and physical aspects of carbon cycling between the atmosphere, land, and ocean reservoirs. These El Niño excursions highlight the possibility of climatic feedbacks in the carbon cycle. They do not mask the increasing secular trend, which mainly tracks the trend in fossil fuel combustion.

The seasonal amplitude also does not remain constant and has a ±10% variation about the mean. Recent analysis reveals a statistically significant positive trend in the seasonal amplitude since 1976 (Bacastow et al., 1985; Enting, 1987). The causes of this amplitude trend have not been unambiguously identified; hypotheses involve shifts in the seasonality of photosynthesis and respiration, faster cycling of carbon as a result of climatic warming, and the direct effects of CO_2 on plants (also referred to as the CO_2 fertilization effect).

Ice-core Data

Bubbles in natural ice contain samples of ancient air. Analysis by gas chromatography and laser infrared spectroscopy of gases occluded in gas bubbles in polar ice has provided a unique reconstruction of atmospheric CO_2 history prior to the modern high-precision instrumental record

(Oeschger and Stauffer, 1986). Deep ice cores have been drilled from many locations in both Greenland and Antarctica.

From the ice-core data, it is deduced that in pre-industrial times, ~1800, the CO_2 concentration was 285 ± 10 ppm and has increased at an accelerating rate since the industrial era (Neftel et al., 1985; Raynaud and Barnola, 1985; Pearman et al., 1986) (Figure 2-2). The ice-core data reveal the possible existence of natural fluctuations of the order of ± 10 ppm occurring at decadal time scales during the last few thousand years (Delmas et al., 1980; Neftel et al., 1982; Stauffer et al., 1985; Raynaud and Barnola, 1985; Oeschger and Stauffer, 1986).

Recent analysis of the 2083-meter-deep ice core from Vostok, East Antarctica, provides for the first time information on CO_2 variations in the last 160,000 years (Barnola et al., 1987; Figure 3-3 in Chapter III). Large CO_2 changes were associated with the transitions between glacial and interglacial conditions. CO_2 concentrations were low (~200 ppm) during the two glaciations and high (~285 ppm) during the two major warm periods. The Vostok ice-core data also emphasize that current levels of atmospheric CO_2 are higher than they have ever been in the past 160,000 years. The CO_2 increase since 1958 is larger than the natural CO_2 fluctuations seen in the Greenland and Antarctic ice-core record.

GMCC Network

The CO_2 concentrations from the ~26 globally distributed sites in the NOAA/GMCC cooperative flask sampling network have been reviewed in Komhyr et al. (1985) and Conway et al. (1988). The distribution for 1981-1985 is shown in Figure 2-3. There are large-scale, coherent, temporal and

FIGURE 2-2

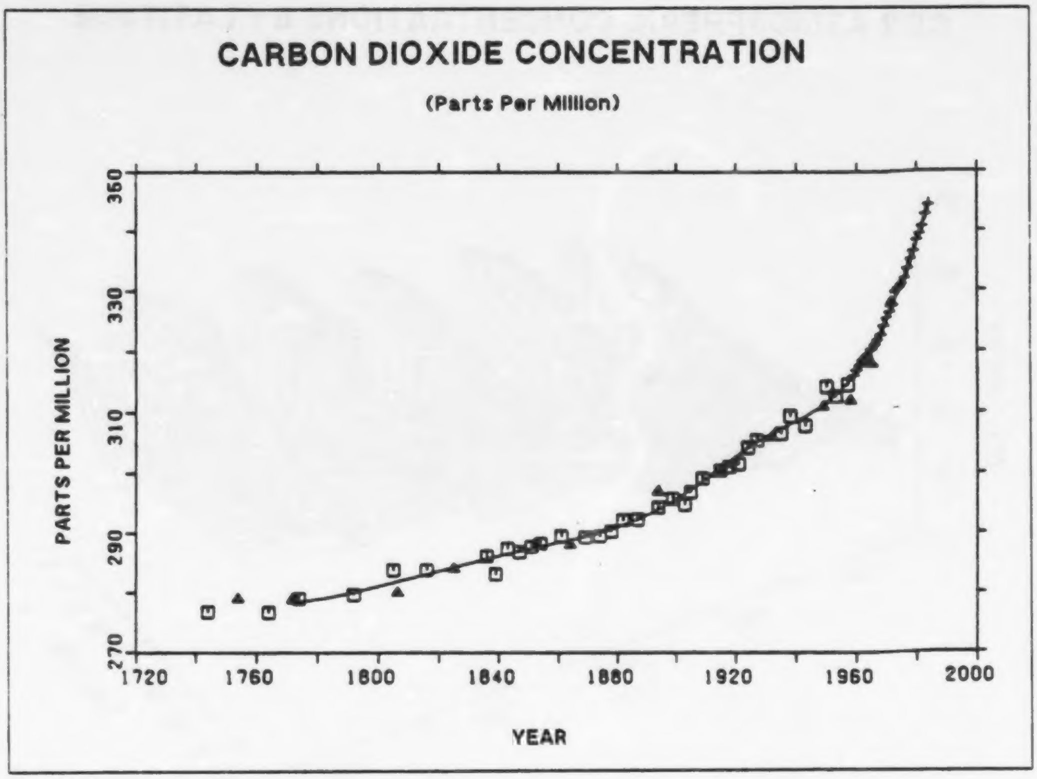

Figure 2-2. The history of atmospheric CO_2 presented here is based on ice core measurements (open spaces, closed triangles) and atmospheric measurements (crosses). The data show that CO_2 began to increase in the 1800s with the conversion of forests to agricultural land. The rapid rise since the 1950s, due primarily to fossil fuel combustion, is at a rate unprecedented in the ice core record, (Sources: Neftel et al., 1985; Friedli et al., 1986; Keeling, pers. communication; as cited in: Siegenthaler and Oeschger, 1987).

FIGURE 2-3

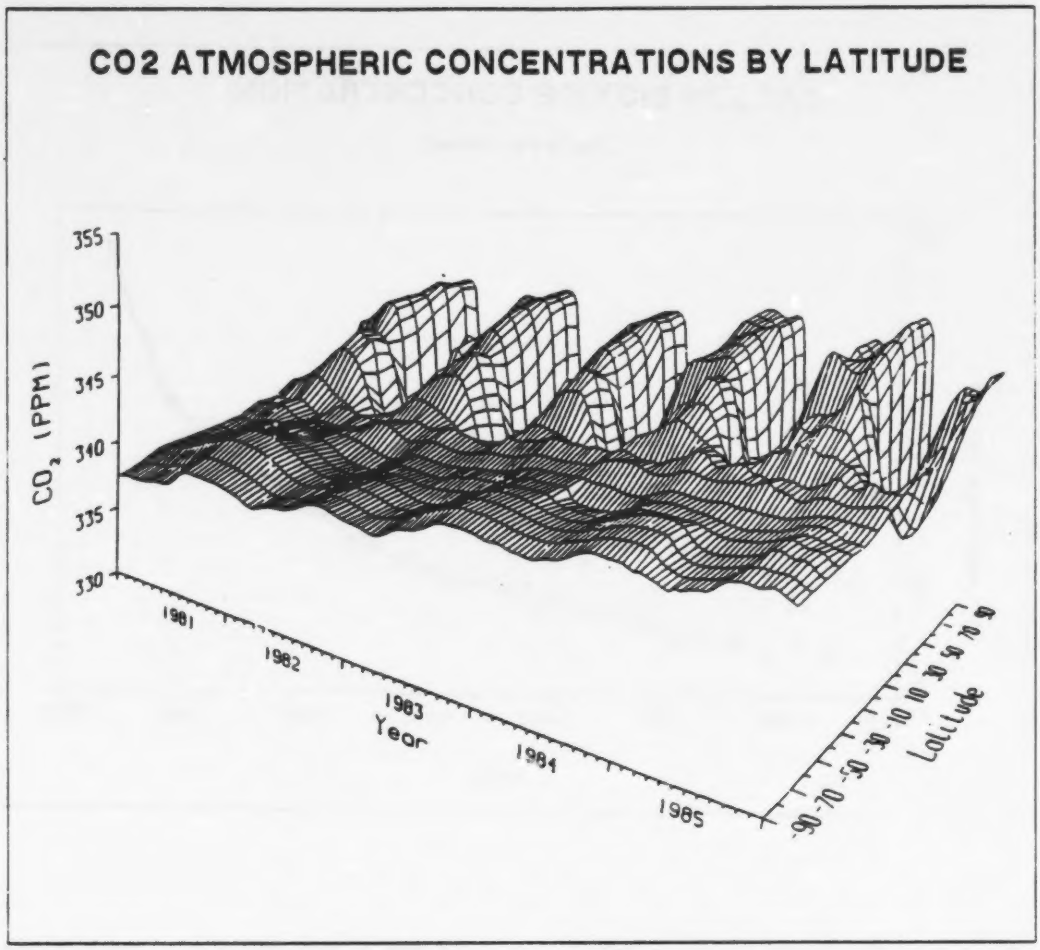

Figure 2-3. The distribution of CO_2 by latitude from 1981-1985 shows that CO_2 is increasing globally. Superimposed on the increasing trend are coherent seasonal oscillations reflective of seasonal dynamics of terrestrial vegetation. The seasonal cycle is strongest at high Northern latitudes, and is weak and of opposite phase in the Southern Hemisphere, reflecting the distribution of terrestrial vegetation. The data are from the NOAA/GMCC flask sampling network. (Sources: Komhyr et al., 1985; NOAA, 1987; Conway et al., 1988.).

spatial variations of CO_2 in the atmosphere. Concentrations of CO_2 at all the stations are increasing at the rate of ~1.5 ppm per year (ppm/yr), similar to the rate of increase at Mauna Loa.

Annually averaged CO_2 concentrations are higher in the Northern Hemisphere than in the Southern Hemisphere. The interhemispheric difference was ~1 ppm in the 1960s and is ~3.2 ppm now, reflecting the Northern Hemisphere mid-latitude source (about 90%) of fossil fuel CO_2. This gradient has remained approximately constant in the past decade. Also evident in the north-south distribution of atmospheric CO_2 is the relative maximum of ~1 ppm in the equatorial regions, caused mainly by the outgassing of CO_2 from the super-saturated surface waters of the equatorial oceans. Although tropical deforestation may also contribute to the equatorial maximum in atmospheric CO_2, models of the global carbon cycle suggest that the observations are inconsistent with a net deforestation source greater than approximately 1.5 Pg C/yr (Pearman et al., 1983; Keeling and Heimann, 1986; Tans et al., 1989).

There is a coherent seasonal cycle at all the observing stations: the Northern Hemisphere cycles resemble that at Mauna Loa. The seasonal amplitude is largest, ~16 ppm, at Pt. Barrow, Alaska, and decreases toward the equator to ~6 ppm at Mauna Loa (Figure 2-3). The CO_2 concentration is flat through the year in the equatorial region and is of opposite seasonality in the Southern Hemisphere. The seasonal cycle in the Northern Hemisphere is caused primarily by seasonal exchanges with the terrestrial biosphere (Fung et al., 1987; Pearman and Hyson, 1986), while in the Southern Hemisphere, oceanic and terrestrial exchanges are equally important in determining the seasonal oscillations in the atmosphere (Pearman and Hyson, 1986). The CO_2 seasonal cycle shows a consistent amplitude increase with time for some sites (Cleveland et al., 1983; Thompson et al., 1986).

The geographical variations of CO_2 growth rates at the GMCC sites show more clearly the El Niño perturbations, as noted already in the Mauna Loa data. For example, the El Niño-caused cessation of upwelling that resulted in the devastation of the fishing industry and marine wildlife in the eastern equatorial Pacific is also evidenced by reduced outgassing of CO_2 to the atmosphere (Feely et al., 1987) and a concomitant decrease in the global CO_2 growth rate (Conway et al., 1988). These variations in the growth rate contain information about the response of the carbon system to climatic perturbations, some of which are under investigation currently.

Sources and Sinks

The atmosphere exchanges CO_2 with the terrestrial biosphere and with the oceans. Averaged over decades, sources must approximately equal sinks if the system is to remain in quasi-steady state; however, the individual flux in each direction may be large (50-100 Pg C/yr). The fluxes of carbon to the atmosphere associated with anthropogenic activities are roughly ten times smaller than the natural fluxes of carbon. However, the anthropogenic fluxes are unidirectional and are thus net sources of carbon to the atmosphere (Figure 2-4).

Fossil Carbon Dioxide

The combustion of fossil fuels, in liquid, solid, or gas forms, is the major anthropogenic source of CO_2 to the atmosphere. A recent documentation and summary of the fossil fuel source of CO_2 is given by Rotty (1987a, 1987b). In 1985, about 5.2 Pg C were released in the form of CO_2 as a result of fossil fuel combustion. Of this, the USA, USSR, and China contributed 23%, 19%, and 10%, respectively (Rotty, pers. communication). The emissions for 1987 were 5.5 Pg C. The history and mix of activities and fuels giving rise to these emissions are discussed in detail in Chapter IV.

FIGURE 2-4

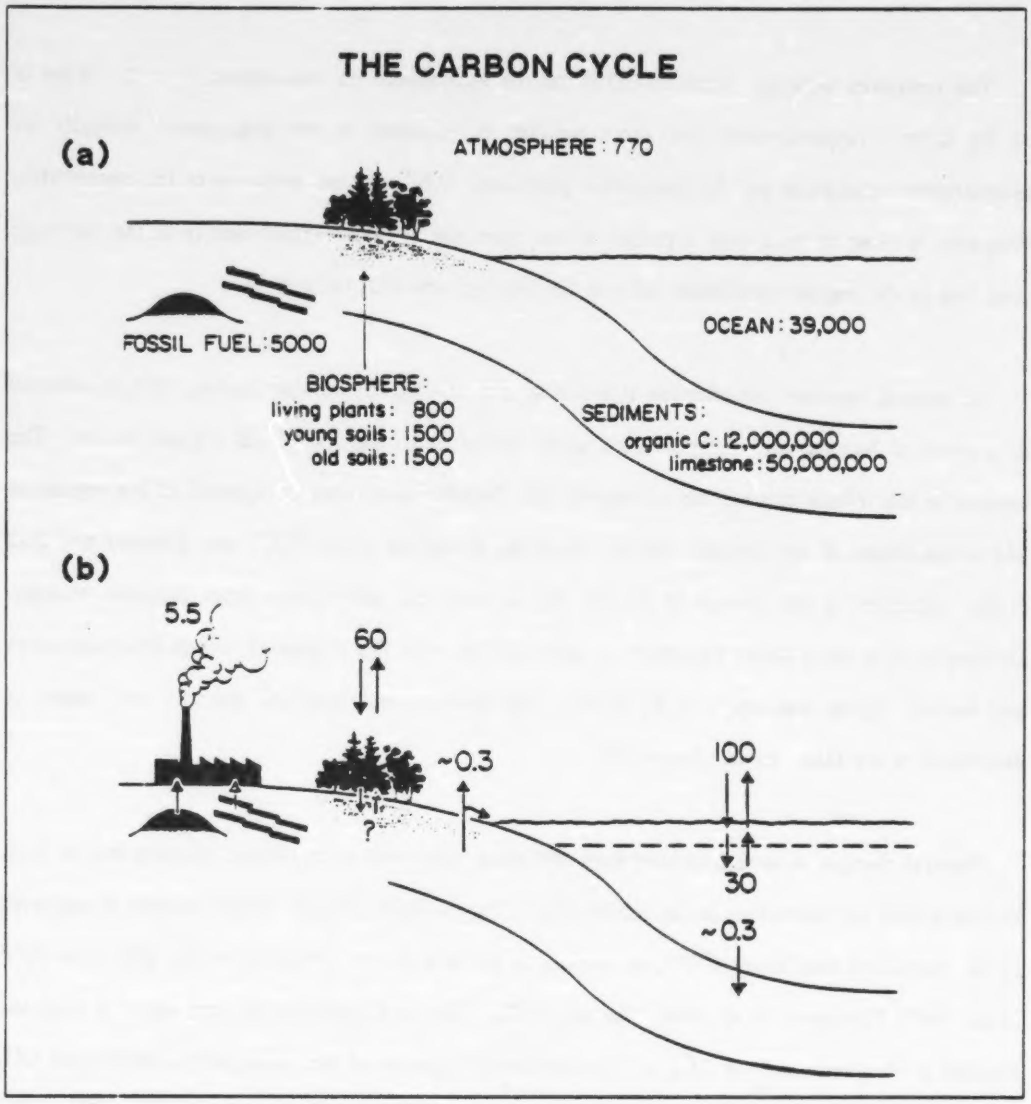
THE CARBON CYCLE
(a)
ATMOSPHERE : 770
FOSSIL FUEL: 5000
OCEAN: 39,000
BIOSPHERE:
living plants: 800
young soils: 1500
old soils: 1500
SEDIMENTS:
organic C: 12,000,000
limestone: 50,000,000
(b)
5.5
60
~0.3
?
100
30
~0.3

Figure 2-4. (a) Major reservoirs of the global carbon cycle. Reservoirs (or stocks) are in units of 10^{15} grams of carbon (Pg C).

(b) Fluxes of carbon, in 10^{15} grams of carbon per year (Pg C/yr).

Source: Adapted from Keeling, 1983.

Biospheric Cycle

The terrestrial biosphere absorbs CO_2 from the atmosphere via photosynthesis on the order of 60 Pg C/yr. Approximately the same amount is returned to the atmosphere annually via heterotrophic respiration and decomposition processes. While the net exchange of the unperturbed biosphere is close to zero over a period of one year, the seasonal asynchronicity of the exchange gives rise to the regular oscillations seen in the atmospheric CO_2 records.

In general, land-use modification is a net source of CO_2 to the atmosphere. CO_2 is released as a result of burning and decay of dead plant matter and oxidation of soil organic matter. The amount of this release exceeds the amount of CO_2 absorbed as a result of regrowth of live vegetation and accumulation of soil organic matter. Recently, Houghton et al. (1987) and Detwiler and Hall (1988) estimated a net source of 0.4-2.6 Pg C/yr to the atmosphere from land-use changes. Deforestation in the tropics accounted for nearly all the flux: The release of carbon from temperate and boreal regions was only 0.1 Pg C/yr. The regional and temporal patterns and causes of deforestation are taken up in Chapter IV.

Natural changes in terrestrial biospheric dynamics may result from climate warming and/or from increased CO_2 concentrations in the atmosphere. The possibility of such natural changes is suggested by the increasing amplitude of CO_2 oscillations in the atmosphere (Bacastow et al., 1985; Cleveland et al., 1983; Thompson et al. 1986; Enting, 1987). The amplitude change may signal a tendency towards a biospheric sink of CO_2, as photosynthesis responds to increasing temperatures and CO_2 concentrations (Pearman and Hyson, 1981; D'Arrigo et al., 1987; Kohlmaier et al., 1987). The amplitude change can also mean increased sources via respiration and decay, which are strongly temperature-dependent processes (Houghton, 1987). Because growth and decay cycles are intimately linked, it is difficult to tell whether atmosphere-biosphere interactions will act as a positive or a negative feedback without further theoretical and field studies (see the discussion of biogeochemical feedbacks in Chapter III).

Ocean Uptake

The exchange of CO_2 across the air-sea interface depends on the degree of CO_2 supersaturation in the surface waters of the oceans and the rate at which CO_2 is transferred across the interface itself. Because of the very nature of shipboard measurements, data on oceanic CO_2 partial pressure (pCO_2) are sparse, both spatially and temporally. Most of the data have come from oceanographic research programs, mainly Scripps Institution of Oceanography in the 1960s (Keeling, 1968), Geochemical Sections (GEOSECS) in the 1970's (Takahashi et al., 1980, 1981), and Transient Tracers in the Oceans (TTO) in the early 1980s (Brewer et al., 1986) and more recently from NOAA survey cruises and from ships of opportunity.

Depending on the regional interplay between temperature, carbon supply from upwelling, and carbon consumption by biological activities, the seasonal cycle of CO_2 in surface water may peak at different times of the year in different oceanic regions (Peng et al., 1987; Takahashi et al., 1986, 1988). This makes it extremely difficult to interpret the sparse oceanic carbon data in the context of the global carbon cycle. The interpretation is aided by data from carbon-14 and other transient tracers in the ocean.

Based on the available data and an understanding of carbon dynamics in the ocean, it is estimated that, on an annual basis, about 90 Pg C/yr is exchanged between the atmosphere and the ocean. This exchange results in a net outgassing of approximately 1 Pg C/yr from the equatorial oceans and a net absorption of about the same amount by the middle to high latitude oceans.

Superimposed on this exchange of 90 Pg C/yr in either direction is the penetration of fossil fuel CO_2 into the oceans, estimated to be ~3 Pg C/yr currently. This oceanic uptake of fossil fuel CO_2 is corroborated by the observations of anthropogenic tracers penetrating gradually into the oceanic thermocline. These tracers include tritium and carbon-14, by-products of nuclear testing in the 1960s, and the chlorofluorocarbons, a recent man-made compound. The magnitude of the oceanic uptake of fossil fuel CO_2 is estimated using numerical models calibrated by tracers. Because of the variability of the oceanic carbon system and the precision of ocean carbon measurements, the oceanic signature of fossil fuel CO_2 has not been demonstrated unambiguously. Takahashi et al. have demonstrated that in the Atlantic, the oceanic pCO_2 increased by 8 ± 8 microatmospheres (μatm) from 1958 to the mid-1970s, an increase that is consistent with estimates from numerical models.

Chemical and Radiative Properties/Interactions

Carbon dioxide is chemically inert in the atmosphere, but it has a very important impact on the Earth's radiation budget and hence on climate and the chemistry of the atmosphere. After water vapor, CO_2 is the most abundant and most significant infrared (IR) absorbing gas in the atmosphere. As discussed in Chapter III, the Earth's climate is determined by the point at which incoming solar (short-wave) radiation is balanced by IR (long-wave) emissions to space from the warm surface and atmosphere. Increasing the concentration of CO_2 and other greenhouse gases in the atmosphere elevates the average surface temperature required to achieve this balance. Doubling the atmospheric CO_2 concentration from 315 to 630 ppm would produce a radiative forcing (the equilibrium surface temperature increase in the absence of climate feedbacks) of 1.2-1.3°C. At current concentrations

THE RADIATIVE EFFECTS OF GREENHOUSE GASES

The radiative effects of greenhouse gases have received a great deal of attention over the last decade. Recent reviews are given by Dickinson and Cicerone (1986) and Ramanathan et al. (1987). In the absence of an atmosphere the Earth would radiate energy to space as a black body with a temperature of about 250° K (-23°C). Figure 2-5 shows the actual emissions, indicating the absorption bands of the major greenhouse gases. Not shown is water vapor, which has continuous absorption throughout this spectral range and dominates all other gases at wavelengths < 8 micrometers (μm) and > 18 μm (Dickinson and Cicerone, 1986). The 15 μm band of CO_2 dominates absorption in the spectral range from 12 to 18 μm, and its absorption in the other parts of the spectrum amounts to 15% or less of its impact in this region.

The shaded region in Figure 2-5, between about 7 and 13 μm, is called the atmospheric window because it is relatively transparent to outgoing radiation: 70-90% of the radiation emitted by the surface and clouds in these wavelengths escapes to space (Ramanathan et al., 1987). Many trace gases happen to have absorption bands in this window region and are therefore very effective greenhouse absorbers. For example, CFCs are as much as 20,000 times more effective than CO_2 per incremental increase in concentration (see Table 2-1).

CO_2 already absorbs most of the radiation emitted from the Earth's surface in the wavelengths where it is active. As a result, each additional molecule of CO_2 added to the atmosphere has a smaller effect than the previous one. Hence, radiative forcing scales logarithmically, rather than linearly, with increases in the concentration of atmospheric CO_2. For example, a 50 ppm increase in CO_2 from 350 to 400 ppm yields a radiative forcing of 0.23°C, while the same increment from 550 to 600 ppm yields a radiative forcing of only 0.16°C. Despite the reduced greenhouse effectiveness of each molecule of CO_2 as concentrations increase, CO_2 will remain the dominant greenhouse gas in the future, responsible for 50% or more of the increased greenhouse effect during the next century for plausible scenarios of future trace gas emissions (Hansen et al., 1988; Chapter V).

FIGURE 2-5

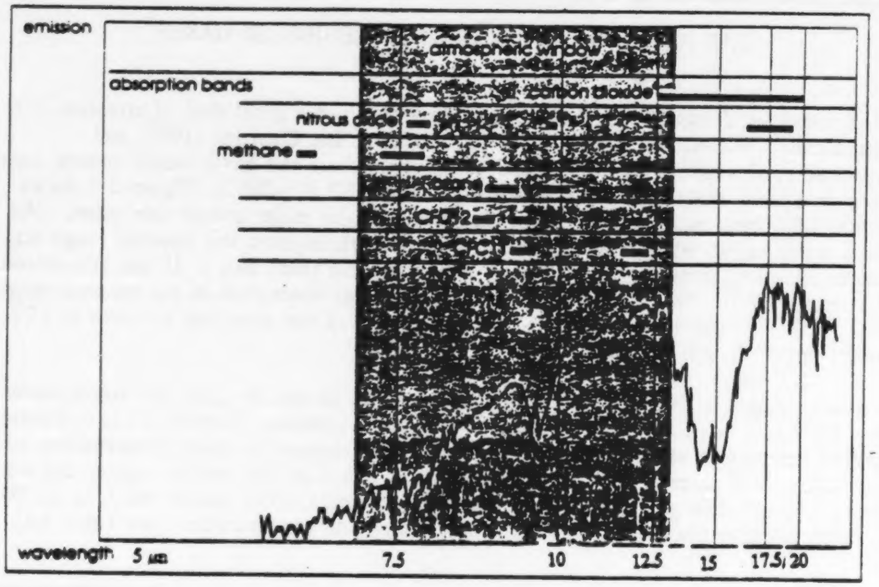

Figure 2-5. Infrared (long-wave) emissions to space from the Earth. Many of the absorption bands of the greenhouse gases fall within the atmospheric window -- a region of the spectrum, between 7 and 13 μm, in which there is little else to prevent radiation from the Earth escaping directly into space. (Source: UNEP, 1987.)

TABLE 2-1

Radiative Forcing for a Uniform Increase in Trace Gases From Current Levels

Compound	Radiative Forcing (No Feedbacks) (°C/ppb)
CO_2	.000004
CH_4	.0001
N_2O	.001
CFC-11	.07
CFC-12	.08
CFC-13	.10
Halon 1301	.10
F-116	.08
CCl_4	.05
$CHCl_3$	.04
F-14	.04
HCFC-22	.03
CH_2Cl_2	.02
CH_3CCl_3	.01
C_2H_2	.01
SO_2	.01

Source: Adapted from Ramanathan et al., 1985.

METHANE

Concentration History and Geographic Distribution

High-precision atmospheric measurements of methane (CH_4) have been made in the past decade at many different locations. The data show clearly that the concentration of methane, 1675 parts per billion by volume (ppb) in 1987, has been increasing at the rate of about 16 ppb per year (Blake and Rowland, 1986, 1988) (Figure 2-6).

Since 1982, air samples from ~25 globally distributed sites of the NOAA/GMCC cooperative network have been analyzed for CH_4 (Steele et al., 1987). In addition to flask sampling, continuous measurements of atmospheric CH_4 are now made at Cape Meares, Oregon (Khalil and Rasmussen, 1983); Pt. Barrow, Alaska; and Mauna Loa, Hawaii (NOAA, 1987).

The data show that CH_4, like CO_2, exhibits very coherent spatial and temporal variations. CH_4 is approximately uniform from mid- to high latitudes in the Southern Hemisphere, and increases northward. The Northern Hemisphere concentration is approximately 140 ppb higher than that in the Southern Hemisphere. The seasonal cycle in the Southern Hemisphere shows a minimum in the summer, consistent with higher summer abundances of the hydroxyl radical (OH) and temperature-dependent destruction rates. In the Northern Hemisphere, the seasonal cycle is more complex, showing the interaction mainly between chemical destruction and emissions from high-latitude peat bogs.

Analysis of air bubbles in ice cores shows that in pre-industrial years, CH_4 was relatively constant at ~700 ppb, from 100,000 years before present (100 kyBP) until the mid-19th century, and exhibited

FIGURE 2-6

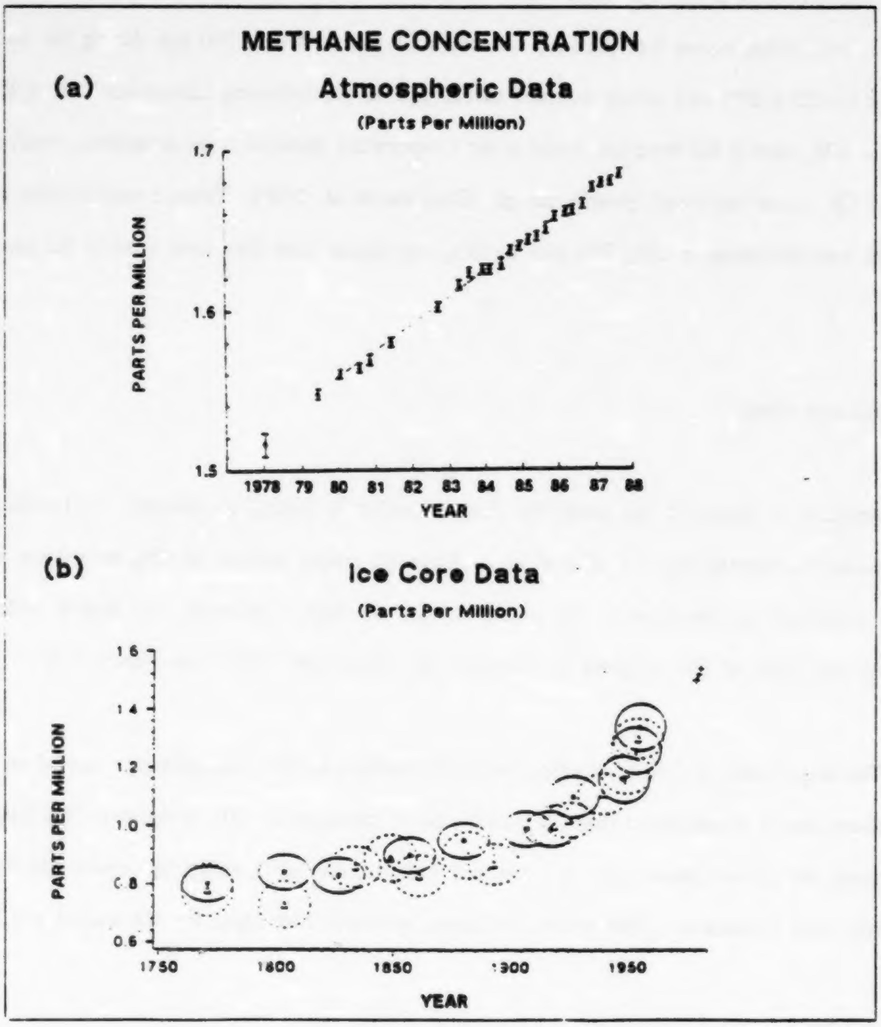

Figure 2-6. Recent measurements of atmospheric CH_4 show that CH_4 has been increasing at the rate of 1%/yr in the last decade (upper panel). Ice core data (lower panel) show that CH_4 was relatively constant in the 1800's, and began to increase rapidly at the beginning of the 20th century. Like CO_2, the recent trend in CH_4 (shown as + + + in the lower panel) is unprecedented in the history of CH_4. The ice core data are from Siple Station, Antarctica. Stars and triangles represent results obtained from melt and dry extraction, respectively. The ellipses indicate the uncertainties in the concentrations as well as in the mean age of the sample. (Sources: Blake and Rowland, 1988; Stauffer et al., 1985.)

a factor of 2.5 increase to its present value in only the last 300 years (Stauffer et al., 1985; Pearman et al., 1986) (Figure 2-6). The 2083-meter ice core recovered by the Soviet Antarctic Expedition at Vostok, Antarctica, shows that the CH_4 concentration was as low as 340 ppb during the penultimate ice age (~155 kyBP) and nearly doubled to 610 ppb in the following interglacial (130 kyBP). The trend in CH_4 closely followed the trend in air temperature deduced from deuterium, confirming the role of CH_4 as an important greenhouse gas (Raynaud et al., 1988). These measurements show that current concentrations of CH_4, like that of CO_2, are higher than they have been in the past 160,000 years.

Sources and Sinks

Methane is produced via anaerobic decomposition in biological systems. It is also a major component of natural gas and of coal gas. While the major sources of CH_4 have been identified, their individual contributions to the global budget are highly uncertain. A recent review of the sources and sinks of CH_4 is given by Cicerone and Oremland (1988) (see Figure 2-7).

The major sink of CH_4 is reaction with OH radicals in the atmosphere.[2] Based on chemical considerations, it is estimated that the global sink of methane is ~510 teragrams (Tg) CH_4/yr.[3] By inference, the annual global source is the sink plus the annual increase, i.e., about 550 Tg CH_4/yr. Cicerone and Oremland (1988) estimate a range of 400 to 640 Tg/yr for the annual global source.

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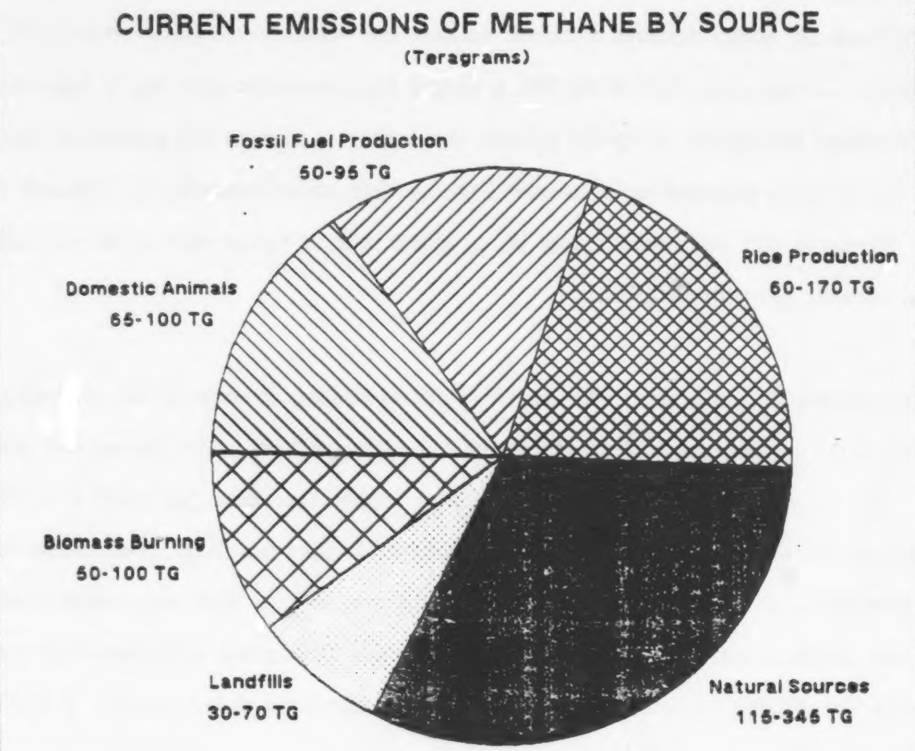
[2] A radical is an atom or group of atoms with at least one unpaired electron, making it highly reactive.

[3] 1 Tg = 1 teragram = 10^{12} grams

FIGURE 2-7



TOP THREE PRODUCERS

Rice Production	Domestic Animals	Fossil Fuel Production
1. India	1. India	1. United States
2. China	2. USSR	2. USSR
3. Bangladesh	3. Brazil	3. China

Figure 2-7. Human activities in the agricultural sector (domestic animals, rice production and biomass burning) and the energy sector (fossil fuel production) are the major sources of atmospheric CH_4. Natural sources, from wetlands, oceans, and lakes, may contribute less than 25% of total emissions. (Sources: Cicerone and Oremland, 1988; Crutzen et al., 1986; Lerner et al., 1988; United Nations, 1987; IRRI, 1986.)

Estimates of methane emissions from natural wetlands have ranged from 11-150 Tg/yr (e.g., Seiler, 1984; Khalil and Rasmussen, 1983). A recent study by Matthews and Fung (1987) estimated that there are 530 million hectares of natural wetlands that account for a global emission of ~110 Tg CH_4/yr. Of this, about 50% of the CH_4 is emitted from productive peat bogs at high latitudes in the Northern Hemisphere, a regional emission that is likely to increase with greenhouse warming. While this study has employed more extensive field data than earlier estimates (e.g., Sebacher et al., 1986; Harriss et al., 1985), uncertainties in the global estimate remain due to the variability of natural wetlands and their CH_4 fluxes.

Rice paddies are environments very similar to natural wetlands in terms of CH_4 production and emission to the atmosphere. In 1984, there were 148 million hectares of rice harvest area globally, with ~50% in India and China. Methane emission studies have been performed in controlled mid-latitude environments (Cicerone et al., 1983; Holzapfel-Pschorn and Seiler, 1986). These studies have identified factors affecting methane fluxes to the atmosphere: inter alia, temperature, soil properties, fertilizer, and irrigation practices. These factors make global extrapolation of methane emissions very difficult. Cicerone and Oremland (1988) estimate a global emission of 60-170 Tg CH_4/yr.

Methane is also produced by enteric fermentation in animals, especially ruminants. The amount of CH_4 produced is dependent on enteric ecology, the composition and quantity of feed, and the energy expenditure of the individual animal. Estimates of emission rates range from 94 kg CH_4/animal/year from West German dairy cattle, to ~35 kg CH_4/animal/year from Indian cattle fed on kitchen refuse, to 5-8 kg CH_4/animal/year from sheep. Using these emission coefficients and population statistics of animals in the world, Crutzen et al. (1986) obtained a global emission of 78 Tg CH_4 for 1983. This emission includes ~5 Tg CH_4 from wild animals and <1 Tg CH_4 from humans. About 75% of the emissions are from cattle and dairy cows. India, the USSR, Brazil, the USA, and China are the five major countries in terms of CH_4 emission from domestic animals (Lerner et al., 1988).

Other natural sources of CH_4 include termites, and exchange with oceans and lakes. The source from termites is highly uncertain and controversial. Estimates of global emissions range from close to zero (Seiler et al., 1984a) to 20 Tg (Fraser et al., 1986b), and as high as 200 Tg CH_4 (Zimmerman et al., 1982, 1984), on the order of half the global emission. The oceanic source is small, estimated to be 5-20 Tg CH_4/yr (Cicerone and Oremland, 1988).

There are several anthropogenic sources of methane. Methane is produced by incomplete combustion during biomass burning. The amount of CH_4 produced depends on the material burned and the degree of combustion. Estimates range from 50-100 Tg CH_4/yr (see Cicerone and Oremland, 1988). While a few studies have attempted to understand and measure CH_4 emission during biomass burning (Crutzen et al., 1979, 1985), extrapolation to a global estimate is difficult because of the lack of global data on area burned, fire frequency, and characteristics of fires. The feasibility of monitoring fires from space (Matson and Holben, 1987; Matson et al., 1987) will improve this estimate significantly.

Methane is also produced in large municipal and industrial landfills, where biodegradable carbon in the refuse is decomposed to form a mixture of CO_2 and CH_4. As in the case of many other CH_4 sources, the fraction of gas produced that escapes to the atmosphere is debated. Recently, Bingemer and Crutzen (1987) estimated that this source produces 45-70 Tg CH_4/yr. These estimates assume that a large fraction of all organic carbon deposited in landfills eventually is subject to methanogenesis and subsequent emission to the atmosphere. Cicerone and Oremland (1988) adopt a range of 30-70 Tg CH_4/yr.

Methane is the major component (~90%) of natural gas, and so the leakage of natural gas from pipelines and the venting of natural gas from oil and gas wells represent sources of CH_4 to the atmosphere. Although natural gas production and consumption statistics are available globally, the nature of this CH_4 source makes it difficult to estimate how much this source contributes to the atmospheric abundance. From U.S. and Canadian natural gas statistics it is estimated that approximately 2-2.5% of the marketable gas is unaccounted for. Assuming that all of the unaccounted for gas is lost to the atmosphere, 25-30 Tg CH_4/yr from line loss is obtained globally (Cicerone and Oremland, 1988). An additional 15 Tg CH_4/yr is estimated from natural gas sources, assuming that ~20% of the gas that is vented and flared at oil and gas wells is not combusted, escaping to the atmosphere as CH_4 (Darmstadter et al., 1987). Together these estimates suggest a source of up to 50 Tg CH_4/yr from natural gas production and consumption. Much of the unaccounted for gas, however, may represent meter discrepancies, and venting of natural gas has been declining in recent years (Darmstadter et al., 1987). Thus a reasonable range for these sources may be 20-50 Tg CH_4/yr.

Methane is also the major component of gas trapped in coal. The percentage of the CH_4 component increases with the age and depth of the coal and is released to the atmosphere during mining and processing/crushing of coal. Globally, the amount of CH_4 in coal is ~0.5% of the mass of coal extracted. This source is estimated to be 15-45 Tg CH_4/yr in 1980 (Darmstadter et al., 1987; Cicerone and Oremland, 1988).

A highly uncertain but potentially large source of CH_4 is methane hydrates in sediments under permafrost and on continental margins (Kvenvolden, 1988). The magnitude of the current CH_4 release from this source is unknown. Climate warming presents the potential for destabilization of the hydrates and subsequent release of CH_4 to the atmosphere (Chapter III).

Chemical and Radiative Properties/Interactions

Methane is the most abundant trace gas in the atmosphere that is active both radiatively and chemically. Although the abundance of methane is 1/200 that of CO_2, CH_4 is a more efficient absorber of thermal radiation than is CO_2: Donner and Ramanathan (1980) and Lacis et al. (1981) estimate that at present levels, an additional molecule of CH_4 will contribute a radiative forcing that is equivalent to that contributed by approximately 25 molecules of CO_2. These radiative transfer calculations suggest that a doubling of atmospheric CH_4 (1.6-3.2 ppm) will contribute a radiative forcing of 0.16°C (Hansen et al., 1988).

The destruction rate of CH_4 is dependent on the amount of OH (and hence water vapor) in the atmosphere as well as on temperature. The lifetime (atmospheric abundance divided by destruction rate) of CH_4 is approximately 10 years, the lifetime being shorter in the tropics. Using estimates of the average concentration of atmospheric hydroxyl radicals derived from measurements of methylchloroform, Prinn et al. (1987) have deduced the average atmospheric lifetime of methane to be 9.6 (+2.2, -1.5) years. The reaction between CH_4 and OH eventually produces CO; CO itself reacts with OH, producing CO_2 (Thompson and Cicerone, 1986). Thus, an increase in the background levels of either CH_4 or CO can reduce OH and the oxidizing power of the entire atmosphere. It is estimated that increases in CO alone from 1960 to 1985 would have lowered OH concentrations in the atmosphere, increased the methane lifetime, and resulted in a 15-20% increase in CH_4 concentrations (Khalil and Rasmussen, 1985; Levine et al., 1985; Thompson and Cicerone, 1986).

Because of the interactions between CO, CH_4, and OH in the atmosphere, it is difficult to predict the effects of climate change on OH destruction of CH_4, as increasing atmospheric water vapor and increased precipitation (and removal of OH reservoirs like nitric acid [HNO_3] and hydrogen peroxide [H_2O_2]) have opposite effects on OH concentrations. Changes in nitrogen oxides (NO_x) and tropospheric ozone (O_3) also strongly affect atmospheric OH (see below).

NITROUS OXIDE

Concentration History and Geographic Distribution

Nitrous oxide (N_2O) is present in minute amounts in the atmosphere but it is nonetheless of great importance. Its concentration is three orders of magnitude less than that of CO_2, but its radiative forcing per molecule is 230 times greater. The first high-precision measurements of atmospheric N_2O in the late 1970s showed an unambiguous increasing trend in its concentration (Weiss, 1981). Continuous measurements at four Atmospheric Lifetime Experiment/Global Atmospheric Gases Experiment (ALE/GAGE) sites have been made since 1979 (Figure 2-8). Flask samples of air from the globally distributed cooperative network of NOAA-GMCC are also being analyzed for N_2O (Thompson et al., 1985; Komhyr et al., 1988).

The ALE/GAGE data show that the mid-1980s concentration of atmospheric N_2O is 310 ppb and that its annual growth rate is ~0.8 ppb per year, or 0.2-0.3% per year. The concentrations at

FIGURE 2-8

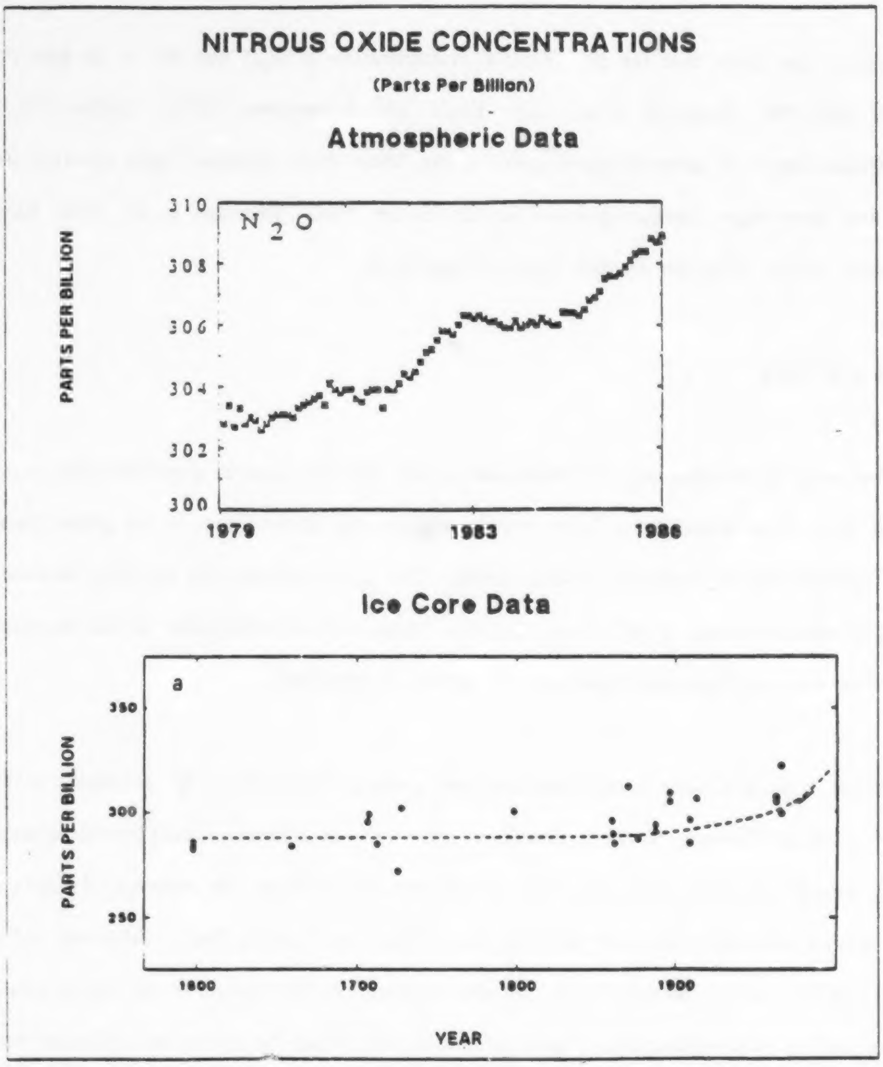


Figure [illegible] 4. Concentration of atmospheric N_2O has been increasing at the rate of 0.25%/yr in the last decade (upper panel). The ice core record shows that N_2O was relatively constant from the 1600's to the beginning of the 20th century, and began increasing rapidly in the last 50 years. (Sources: Khalil and Rasmussen, 1987; Pearman et al., 1986.)

the two Northern Hemisphere sites are 0.8 ppb higher than those at the Southern Hemisphere sites, suggesting the dominance of a northern source.

Ice-core data show that the preindustrial concentration of N_2O was 285 ± 10 ppb averaged between 1600-1800 (Pearman et al., 1986; Khalil and Rasmussen, 1987). Unlike CO_2, whose concentration began to increase significantly in the 1800s, N_2O remained fairly constant until the 1900s, and then began increasing more rapidly in the 1940s (Pearman et al., 1986; Khalil and Rasmussen, 1987). (See the ice-core data in Figure 2-8).

Sources and Sinks

While a lot of progress has been made during the last five years in quantifying the sources and sinks of N_2O in the atmosphere, there remain considerable uncertainties in the global budget and in the contributions of individual source terms. The uncertainties arise not just because of the scarcity of measurements of N_2O fluxes, but also because of the complexity of the biogeochemical interactions and heterogeneous landscape where N_2O is produced.

Nitrous oxide is simultaneously produced and consumed in soils via the metabolic pathways of denitrification, nitrification, nitrate dissimilation, and nitrate assimilation. These processes are affected by various environmental parameters such as temperature, moisture, the presence of plants, and the characteristics and composition of the soils (e.g., Seiler and Conrad, 1987; Sahrawat and Keeney, 1986). The flux of N_2O to the atmosphere also depends on the location of the N_2O-producing and N_2O consuming microorganisms and their relative activity within the soil column (Conrad and Seiler, 1985). Because of the complexity of the N_2O production and destruction processes, and the inherent heterogeneity of soils, it is difficult to estimate the contribution of natural soils to the global N_2O

budget. Slemr et al. (1984) calculated N_2O emissions from natural temperate and subtropical soils to be 4.5 Tg N/yr. Recent measurements (Livingston et al., 1988; Matson and Vitousek, 1987) show that N_2O emission rates from tropical soils are higher than those from temperate soils and that a relationship exists between the N_2O flux and the rate of nutrient cycling in the tropical forest soils. However, no budget of N_2O emissions from tropical soils has been attempted. Seiler and Conrad (1987) give a very tentative estimate of 6 ± 3 Tg N/yr from natural soils globally.

Measurements of supersaturation of N_2O in the oceans indicate that the oceans contribute additional N_2O to the atmosphere, though in smaller quantities (Seiler and Conrad, 1981; Weiss, 1981). Seiler and Conrad (1987) estimated the oceanic contribution to be 2 ± 1 Tg N/yr.

Little is known about N_2O emissions from terrestrial freshwater systems. Extrapolating from measurements in the Netherlands and in Israel of elevated N_2O levels in aquifers contaminated by the disposal of human or animal waste, cultivation, and fertilization, Ronen et al. (1988) estimated a global source 0.8-1.7 Tg N/yr from contaminated aquifers.

Nitrous oxide is also produced during combustion, but the importance of this source is unclear at this time. A recent study of this N_2O source was reported by Hao et al. (1987) who found that the amount of N_2O in flue gases was correlated with the nitrogen content of fuels. N_2O emission rates were highest during coal combustion, lower when oil was used as the fuel, and lowest when the fuel was natural gas. They found that in conventional single-stage boilers, on average, 14% of fuel nitrogen was converted to N_2O during combustion. Conversion of fuel nitrogen to N_2O was much less efficient (2-4%) in a two-stage experimental combuster and in wood fires. They also found consumption of N_2O in fuel-rich flames with low air-fuel ratios, reducing significantly the emission factor. Using statistics on solid- and liquid-fuel production, they estimated an emission of 3.2 Tg

N_2O-N in 1982. Very recent studies, however, suggest that many of the N_2O measurements reported in the literature have been affected by a sampling artifact. A reaction between water, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) generates N_2O in sample cylinders over a period of hours, sometimes increasing N_2O concentrations by more than an order of magnitude unless the samples are carefully dried or N_2O is measured immediately (Muzio and Kramlich, 1988). Reanalysis of measurements made in the U.S., excluding those that were apparently affected by this reaction, found no significant difference between N_2O emissions from gas and coal-fired boilers (Piccot, pers. communication). Recent measurements conducted by EPA with an on-line analyzer confirm this finding: In both utility and small experimental boilers N_2O concentrations in the exhaust gases were always less than 5 ppm and generally less than 2 ppm (Hall, pers. communication). This suggests that the relationship between N_2O and fuel-nitrogen found by Hao et al. (1987) may have actually been due to differences in SO_2 and NO_x emissions. Emissions of N_2O do appear to vary with combustion technology. Preliminary measurements suggest that fluidized-bed combusters and catalyst-equipped automobiles may have substantially elevated N_2O emissions (De Soot, pers. communication). Total N_2O emissions from fossil-fuel combustion cannot be estimated with any confidence at this time, but may be closer to 1 Tg N/yr than to 3 Tg N/yr (Chapter V).

The addition of nitrogenous fertilizers to soils enhances the emission of N_2O and other nitrogen gases to the atmosphere. This emission depends on temperature, soil moisture, rainfall, fertilizer type, fertilizer amount, and the way the fertilizer is applied. It also depends on the properties of the soils and the crops grown. The fraction of fertilizer nitrogen lost to the atmosphere as nitrous oxide ranges from ~0.001-0.05% for nitrate, ~0.01-0.1% for ammonium fertilizers, to ~0.5->5% for anhydrous ammonia. With a global consumption of approximately 70.5 million tons nitrogen as nitrogenous fertilizers in 1984, an N_2O contribution of 0.14-2.4 Tg N/yr is estimated. Although the estimated N_2O emissions associated with the use of nitrogenous fertilizers are small compared with those from natural sources, they are, nonetheless, a source subject to rapid growth.

Land-use modification in the tropics may also contribute N_2O to the atmosphere. N_2O is produced during biomass burning, but because direct estimates of total N_2O emissions are difficult, N_2O emissions are estimated by ratios with emissions of CO_2 or other nitrogen gases. Crutzen (1983) estimated this source to be 1-2 Tg N/yr, although the accuracy of this estimate is highly uncertain.

Recently, Bowden and Bormann (1986) found enhanced N_2O fluxes to the atmosphere from cleared areas in a temperate forest and elevated N_2O concentration in ground water adjacent to the cut watershed. Similarly, tenfold increases in N_2O fluxes are found in pastures and forest clearings in the Amazon (Matson, pers. communication). Robertson and Tiedje (1988) postulate, on the basis of observations in Central America, that the loss of primary tropical rain forest may decrease the emissions of N_2O to the atmosphere. These studies suggest that rapid deforestation in the tropics may significantly alter the N_2O budget, although an estimate of its contribution to the global budget has not been attempted.

Chemical and Radiative Properties/Interactions

N_2O has a low concentration in the atmosphere, and its rate of increase is much smaller than that of the other trace gases. Yet it still plays an important role in the radiative and chemical budgets of the atmosphere. The seemingly small growth rate, ~0.25%/year, is the result of a large imbalance (~30%) between the sources and sinks. The extremely long lifetime of N_2O, ~160 years, means that the system has a very long memory of its emission history.

Nitrous oxide is an effective greenhouse gas. The radiative forcing of one molecule of N_2O is equivalent to that of ~230 molecules of CO_2; a doubling of N_2O and a doubling of CH_4 yield approximately the same radiative forcing, even though the N_2O concentration is less, by a factor of 5, than that of CH_4. A 25% increase in the current burden of N_2O in the atmosphere will yield a radiative forcing of 0.07°C.

Nitrous oxide is not chemically reactive in the troposphere. However, its destruction in the stratosphere, by photolysis and by reaction with atomic oxygen in the excited state $[O(^1D)]$, makes N_2O the dominant precursor of odd nitrogen in the stratosphere. Thus, an increase in N_2O would lead to an increase in stratospheric NO_x, which would significantly influence stratospheric ozone chemistry.

CHLOROFLUOROCARBONS (CFCs)

Concentration History and Geographic Distribution

High-precision measurements of CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) began in 1971 with the development of electron capture detector/gas chromatograph techniques (Lovelock, 1971). Like CO_2 and CH_4, surface measurements have consisted of high-frequency observations at a few dedicated sites as well as flask samples of air collected from a global network of stations or from irregular global transects.

High-frequency *in situ* measurements of surface concentrations have been or are currently being made at the five coastal/island stations of the Atmospheric Lifetime Experiment/Global Atmospheric Gases Experiment (ALE/GAGE) (Cunnold et al., 1986; Prinn et al., 1983; Rasmussen and Khalil, 1986; Simmonds et al., 1987). In addition, analysis of CFC concentrations in the flask samples of air collected at the NOAA-GMCC globally distributed network of sites have begun at the GMCC facility in Boulder (Thompson et al., 1985; NOAA, 1987).

CFC-12 is the most abundant halocarbon in the atmosphere. Its average tropospheric concentration in 1986 was 392 parts per trillion by volume (ppt), corresponding to a total burden of about 7.6 Tg. Its concentration is increasing at 4%/yr.

With a total burden of about 5.0 Tg, CFC-11 is the second most abundant halocarbon in the atmosphere. Its average concentration in 1986 was 226 ppt, and is also increasing at 4%/yr.

The other important halocarbons include methyl chloroform (CH_3CCl_3), 125 ppt in 1986, increasing at ~6%/yr; carbon tetrachloride (CCl_4), 121 ppt in 1982, increasing at 1.3%/yr; HCFC-22 (formerly denoted CFC-22; $CHClF_2$), ~100 ppt in 1986, increasing at 7%/yr; and Halon-1211 (CF_2C1Br), ~2 ppt in 1986 and increasing at >10%/yr (Prinn, 1988).

Sources and Sinks

CFCs are the product solely of the chemical industry. CFC-11 is used in blowing plastic foams and in aerosol cans. CFC-12 is used primarily in refrigeration and aerosol cans. Comprehensive data on production of CFC-11 and CFC-12 are published by the Fluorocarbon Program Panel (FPP) of the Chemical Manufacturers Association (CMA). The peak year for CFC production was 1974, in which a total of 812.5 gigagrams (Gg) of CFC-11 plus CFC-12 was produced.[4] The annual total CFC production decreased for a number of years following a ban on non-essential aerosol uses in the United States, Canada, and Sweden. Non-aerosol uses have continued to increase, however, and the total has risen rapidly in recent years, reaching 703.2 Gg in 1985. Of this total about 70% was consumed by the U.S., the European Economic Community, and Japan (see Figure 4-9 in Chapter IV).

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[4] 1 Gg = 10^9 grams = 10^6 Kg

The CMA data do not cover the USSR. The FPP has estimated Soviet production; however, these estimates are considered unreliable. Data for China and the countries of Eastern Europe are lacking entirely, rendering large uncertainties in the magnitude of world emissions. Cunnold et al. (1986) and Fraser et al. (1983) have found the measured trend of CFC-11 and CFC-12 concentrations is relatively consistent with the CMA estimates of CFC-11 release but not CFC-12 release, which suggests that the USSR and Eastern Europe contribute a substantial amount to CFC-12 emissions.

Methyl chloroform (CH_3CCl_3) is widely used in the manufacturing industry as a solvent for degreasing, CFC-113 is used in the electronics industry, mainly for circuit board cleaning, and HCFC-22 is used mainly in refrigeration. The sources of these gases have been estimated in various studies, but a survey of sources--equivalent to that conducted for CFC-11 and CFC-12 -- has not been done.

Fully halogenated CFCs (those that contain no hydrogen) are destroyed almost solely by photolysis in the stratosphere. The atmospheric lifetimes of CFCs estimated from the ALE/GAGE analyses are 111^{+22}_{-44} years for CFC-12, 73^{+31}_{-17} years for CFC-11, $6.3^{+1.2}_{-0.9}$ years for methyl chloroform, and approximately 40 years for carbon tetrachloride. Compounds containing hydrogen (HCFCs) react with OH in the troposphere and have lifetimes on the order of 20 years or less.

Chemical and Radiative Properties/Interactions

CFCs absorb infrared radiation in the window region of the atmospheric spectrum (Figure 2-5). Although CFCs are present in minute amounts in the atmosphere, together they are one of the dominant greenhouse gases. They have the highest annual fractional increase (~5%/yr) of all the greenhouse gases. Furthermore, the radiative forcing due to each additional molecule of CFC is equivalent to that due to about 30,000 molecules of CO_2, and at present levels increases linearly with the concentration (Ramanathan et al., 1987). A 2 ppb increase in both CFC-11 and CFC-12 will contribute a radiative forcing of 0.3°C, equivalent to that from a 65 ppm increase in CO_2. In the 1980s, CFC-11 and CFC-12 together will contribute about 15% of the increase in global greenhouse forcing.

Chlorinated and brominated compounds contribute chemically active halogens into the atmosphere, where they are broken down by solar ultraviolet radiation or by reaction with OH. In addition to CFC-11 and CFC-12, these species include methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4), and methyl halides (CH_3Cl, CH_3Br, and CH_3I). Also important are two rapidly increasing chlorofluorocarbons, CFC-113 ($C_2Cl_3F_3$) and HCFC-22 ($CHClF_2$). Halocarbons with at least one hydrogen, such as methyl chloroform and HCFC-22 are destroyed primarily by reaction with OH radicals in the troposphere. Long-lived species survive the 1-3 year transport time from the surface up to stratospheric levels to play a critical role in ozone photochemistry. All of these species can contribute to the stratospheric burden of chlorine, but the longer-lived CFCs can accumulate, reaching higher concentrations before a steady state balance is achieved.

The dissociation products of halocarbons are the dominant sources of chlorine (Cl) and fluorine (F) for the stratosphere (WMO, 1985), which are major components in the catalytic cycles that control ozone abundance. Ground-based data and aircraft data of trends for major halocarbon reservoirs (HCl, HF, ClO) are highly uncertain. Within the limits of the uncertainties, the estimated trends in these species were not in disagreement with trends in the source gases themselves.

OZONE

Concentration History and Geographic Distribution

Ozone (O_3) is both produced and destroyed *in situ* in the atmosphere. Unlike the other trace gases, the vertical distribution of O_3 in the atmosphere is of prime importance in determining its radiative and chemical effects (Figure 2-9).

Ozone sondes from a diverse and globally distributed network provide our only record of possible trends in the vertical distribution of tropospheric O_3. A review of ozone sonde and surface data have been given by Logan (1985), Tiao et al. (1986), and more recently by Crutzen (1988). Since the 1970's, surface O_3 concentrations are measured routinely at the four continuous monitoring stations operated by NOAA-GMCC: Pt. Barrow, Alaska; Mauna Loa, Hawaii; American Samoa; and the South Pole (see e.g. NOAA, 1987). NOAA-GMCC also participates in international cooperative ozone sonde profiling activities.

The O_3 data taken near populated and industrial regions in the 1930's to the 1950's generally showed an annually averaged concentration of 10-20 ppb at the surface, with a seasonal cycle that peaked in summer. The data showed a generally increasing trend, especially in the summer, in surface concentrations of O_3 at sites in western Europe, the USA and northern Japan. For example, a factor of two increase, from ~30 ppb in 1933 to ~60 ppb in the 1980s, is found in the summer

FIGURE 2-9

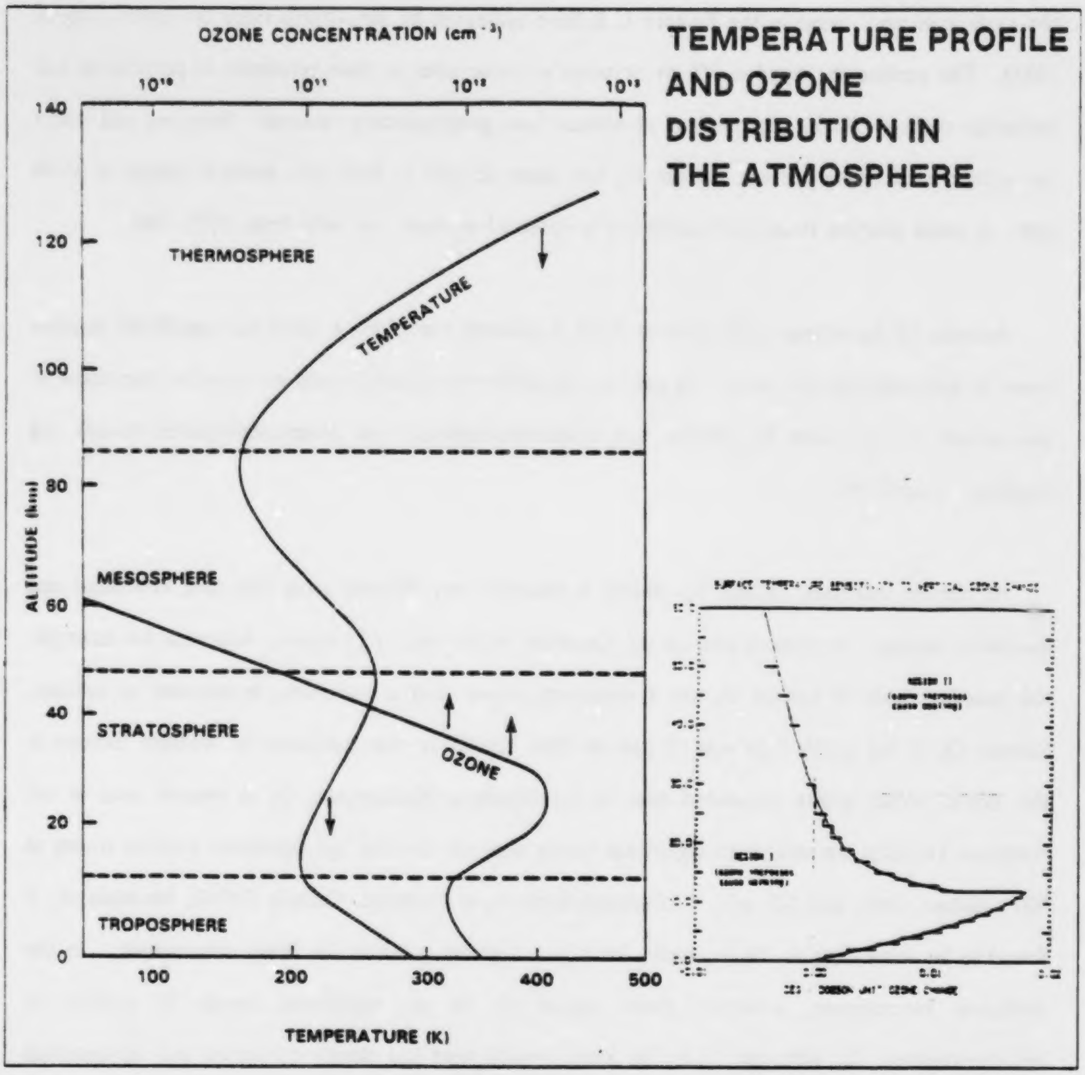

Figure 2-9. On the left, temperature profile and ozone distribution in the atmosphere. On the right, sensitivity of global surface temperature to changes in vertical ozone distribution. Ozone increases in Region I (below ~30 km) and ozone decreases in Region II (above ~30 km) warm the surface temperature. The results are from a 1-D radiative transfer model in which 10 Dobson unit ozone increments are added to each layer. The heavy solid line is a least square fit to step-wise calculations. (Sources: Watson et al., 1986; Lacis et al., no date)

concentrations in south Germany and Switzerland. Similarly, summertime concentrations of O_3 at the surface in rural areas in the Eastern U.S. have increased by 20%-100% since the 1940s (Logan, 1985). The surface O_3 trend is 1%/yr or more at those sites in close proximity to population and industrial centers. At Pt. Barrow and at Mauna Loa, geographically removed from but still under the influence of urban centers, surface O_3 was about 25 ppb in 1986 with summer values of 35-40 ppb. A small positive trend (0.7 ± 0.5%/yr) is detected at these two sites from 1973-1986.

Analysis of the ozone sonde data at these populated sites show a small but significant positive trend in mid-tropospheric ozone. In general, the mid-tropospheric trends are smaller than those at the surface of the same O_3 profile, and upper-tropospheric and lower-stratospheric trends are negative, ~-0.5%/yr.

At remote locations, surface O_3 exhibits a behavior very different from that near populated and industrial regions. At remote sites in the Canadian Arctic and in Tasmania, Australia, for example, the seasonal cycle of surface O_3 has a minimum, rather than a maximum, in summer or autumn. Surface O_3 at the South Pole was 20 ppb in 1986, similar to that measured in Western Europe in the 1930s. Also, unlike populated sites in the Northern Hemisphere, O_3 at remote sites in the Northern Hemisphere exhibit no significant trends near the surface, but significant positive trends at 700 millibars (mb) and 500 mb. Mid-tropospheric O_3 at Resolute, Canada (75°N), for example, is found to be increasing at 1%/yr, while there is a negative trend in the lower stratosphere. In the Southern Hemisphere, however, there appear to be no significant trends in surface or mid-tropospheric O_3, although O_3 in the lower stratosphere has clearly decreased and the seasonal cycle at the South Pole has doubled in amplitude.

The recent record of O_3 concentrations in the upper atmosphere has been reviewed by a NASA panel of experts (Watson et al., 1988). They report a general decreasing trend in the total O_3 concentration in the entire atmospheric column from 1969 to 1986, the period of examination. Ground-based Dobson instruments, located mainly between 30 and 64 degrees in the Northern Hemisphere, show a total decrease of 1.7-3.0% in 17 years in the annually averaged O_3 concentration of the entire atmospheric column. The decrease was more rapid in the winter months, from December to March. Satellite data, calibrated by coincident Dobson measurements, show a decrease of about 2-3% from October 1978 to October 1985 in the column O_3 concentrations between 53°S and 53°N. The observations of stratospheric O_3 in the Northern Hemisphere indicate that O_3 abundances have declined over the past 20 years. The rate of decrease in the summer is consistent with the predicted change due to CFCs. However, the measured ozone loss poleward of 40°N in winter is greater than that predicted by theory (Rowland, 1989). This depletion of O_3 in the north is not associated with the unusual chemistry of the Antarctic ozone hole and may be the beginning of a truly global decline.

Sources and Sinks

Ozone is not directly emitted by human activity, but its concentration in the troposphere and stratosphere is strongly governed by anthropogenic emissions of NO_x, hydrocarbons, and CFCs, among others. Because of the short lifetimes of NO_x and many of the other chemical species important in tropospheric O_3 chemistry, O_3 concentrations exhibit large variability horizontally, vertically and temporally. Its annual concentration, seasonal cycle, as well its trend have different behaviors in different parts of the globe so that the observations from a few regions cannot be viewed as globally representative. Global trends in tropospheric O_3 cannot be unambiguously extracted from trends in column O_3 either. Stratospheric O_3 dominates the column abundance and its decreasing trend may obscure positive or negative trends in tropospheric ozone. The difficulty in determining the globally representative trend in tropospheric O_3 translates into uncertainties in the O_3 contributions to the greenhouse warming.

Chemical and Radiative Properties/Interactions

Radiative forcing of O_3 is more complex than that of the other greenhouse gases because (1) O_3 is the major source of atmospheric heating due to ultraviolet and visible absorption bands, in addition to being a greenhouse gas, and (2) O_3 trends are not uniform in the atmosphere -- anthropogenic effects are expected to include upper stratospheric losses, lower tropospheric increases, and latitude dependent changes in the lower stratosphere and upper troposphere.

Radiative transfer calculations reveal that the climate forcing due to an O_3 perturbation changes sign at 25-30 km altitude (see Figure 2-9). Ozone increases below this level lead to surface warming because its greenhouse effect dominates its impact on solar radiation, while O_3 added to the stratosphere above ~30 km increases stratospheric absorption of solar energy at the expense of solar energy that would otherwise have been absorbed at lower altitudes. On a per molecule basis, the O_3 changes with by far the largest net effect on surface temperatures are those near the tropopause where the temperature contrast between absorbed and emitted thermal radiation is greatest. O_3 changes near the surface produce little greenhouse forcing since the outgoing thermal radiation absorbed is of nearly the same temperature as the radiation emitted by surface ozone.

While the radiative effects of O_3 are understood theoretically, quantifying surface temperature changes due to O_3 changes is difficult because of the uneven data and the lack of global coverage in the observations. Available ozone trend data are limited to northern mid-latitudes. Based on the lifetimes, on the order of 10 to 200 years; and they accumulate in the atmosphere until their rate of chemical destruction balances their emissions. The chemistry of the stratosphere and troposphere provides the oxidizing power to destroy the majority of trace pollutants in the Earth's atmosphere (a major exception is CO_2, see above). We outline below those primary and secondary components of the Earth's atmosphere that affect the chemically reactive gases and note changes that may have occurred in the recent past and those possible in the future.

Global Tropospheric Chemistry

In the troposphere, many species are removed in a chain of reactions beginning with the hydroxyl radical, OH, and ending with the deposition or rainout of a soluble compound, or with the complete oxidation of the original compound (i.e., net: $CH_4 + 2O_2 ==> CO_2 + 2H_2O$). For CH_4, most hydrocarbons, and halocarbons containing a hydrogen atom (e.g., anthropogenic HCFCs such as $CHClF_2$), the chemical lifetime will vary inversely with the suitably averaged global OH concentration.

The OH radicals in the troposphere are short-lived (<1 sec) and are produced by sunlight in the presence of O_3 and H_2O; they are consumed rapidly by reaction with CO, CH_4, and other hydrocarbons. Moderate levels of nitrogen oxides (NO_x: NO and NO_2) can play an important role in recycling the odd-hydrogen (HO_x) from HO_2 to OH, thus building up the concentrations of OH; but high levels of NO_x can reduce both OH and O_3. The short lifetime of OH means that, when we integrate the loss of even a well-mixed gas like CH_4 against consumption by reaction with OH, we are integrating over the myriad of conditions of the troposphere in terms of sunlight, O_3, H_2O, CO, CH_4, NO_x, and others. These tropospheric conditions vary over scales that range from smooth in latitude and height, to irregular in plumes downwind from metropolitan areas. At present we do observed decreases in O_3 in the upper troposphere and lower stratosphere, which outweighed the warming caused by decreases in the upper stratosphere and by increases in O_3 in the lower troposphere, Lacis et al. (no date) find that during the 1970s, surface cooling resulted from these O_3 changes. This cooling was equal in magnitude to about half of the warming contributed by CO_2 increases during the same time period. These results differ from previous assessments (e.g., Ramanathan et al., 1985; Wang et al., 1988) that were based on one-dimensional photochemical model results which predict ozone increases in the lower stratosphere and upper troposphere, and thus produce surface warming. Predictions of two-dimensional photochemical models for increases in CFCs suggest that ozone should decrease in the lower stratosphere at middle and high latitudes, but increase in the tropics (Ko et al., 1984; WMO, 1985). This implies a strongly latitude-dependent climate forcing for O_3 distributional changes with surface cooling in the middle and high latitudes and warming in the tropics.

The global nature of O_3 changes in the upper troposphere and lower stratosphere cannot be deduced, at this point, from current observations. This makes highly uncertain the evaluation of O_3 contributions to the global greenhouse warming. Lacis et al. (no date) note that even the best sampled O_3 data from mid-latitudes in the northern hemisphere are of uneven quality, and that the associated trends have large uncertainties and may not be globally representative.

OTHER FACTORS AFFECTING COMPOSITION

In addition to those greenhouse gases cited above that have a direct impact on the radiative balance of the Earth, we must consider those forces that control the chemical balance of the atmosphere, in turn controlling the abundance of greenhouse gases. With the exception of ozone, the greenhouse gases are generally not very reactive in the atmosphere; they have long chemical not have adequate models for OH that can describe these varied conditions and accurately integrate the global loss of a greenhouse gas such as CH_4.

In spite of these problems in modeling the chemically complex, heterogenous conditions of the global troposphere, we do understand tropospheric chemistry sufficiently to make some simple generalizations:

- Most loss of CH_4 occurs in marine environments, particularly in the tropics and subtropics, remote from the influence of urban areas and the continental boundary layer,
- Increasing concentrations of CO and CH_4 will reduce global or hemispheric levels of OH,
- Large scale perturbations to tropospheric O_3 and H_2O (from climate change) may have equal impact on OH concentrations,
- Changes in anthropogenic emissions of NO_x are expected to have only a moderate direct impact on globally integrated OH, but may lead to more significant increases in Northern Hemispheric O_3.

Carbon Monoxide

Carbon monoxide (CO) has a lifetime of about one month in the tropics that becomes indefinitely long in winter at high latitudes. The globally averaged destruction of CO corresponds to an estimated lifetime of 3 months. Carbon monoxide is lost almost exclusively through tropospheric reactions with OH (and in this non-linear system, CO is also a major sink for OH). There are some estimates of plant/soil uptake of CO, but these are not of major significance.

Detailed observations of CO concentrations are available over the past decade (Dianov-Klokov and Yurganov, 1981; Khalil and Rasmussen, 1988) and there are sporadic measurements since 1950 (Rinsland and Levine, 1985). These data indicate that CO concentrations have grown modestly, but consistently (1-2%/yr) in the northern mid-latitudes over the last few decades. There is no convincing evidence for growth in the Southern Hemisphere (Seiler et al., 1984b). This pattern is consistent with a growing anthropogenic source, since the short lifetime precludes significant interhemispheric transport. Since CH_4 concentrations have also increased similarly (about 1%, as noted above), we would expect a similar change of opposite sign in tropospheric OH.

Nitrogen Oxides

One form of odd-nitrogen denoted as NO_x is defined as the sum of two species, NO + NO_2. NO_x is created in lightning, in natural fires, in fossil fuel combustion, and in the stratosphere from N_2O. The NO_x levels over the continental boundary layer and in the aircraft flight lanes of the Northern Hemisphere are likely to have increased over the last several decades. Nevertheless, the levels of NO_x in the clean marine environment are so low that they might be accounted for entirely by natural sources (i.e., lightning, fires, stratospheric HNO_3).

The anticipated changes in NO_x levels over limited regions of the Northern Hemisphere are expected to have only a small direct effect on the globally integrated OH concentration. A more important impact of NO_x emissions is likely for tropospheric O_3, where a substantial fraction of the global tropospheric ozone production is predicted to take place in small regions with elevated levels of NO_x and hydrocarbons (Liu et al., 1987). These issues are unresolved and are currently the focus of photochemical studies with multi-dimensional tracer models.

Stratospheric Ozone and Circulation

Some species such as N_2O and CFCs do not react with OH, and these gases are destroyed only in the stratosphere by short-wavelength ultraviolet light and by reactions with the energetic state of atomic oxygen, $O(^1D)$. For CFCs and N_2O the abundances will be perturbed by changes in the rate of stratosphere-troposphere circulation and changes in the stratospheric O_3 that shields the solar ultraviolet radiation. Major perturbations to stratospheric O_3 and circulation may also alter the concentrations of tropospheric O_3, since the stratosphere represents a major source for this gas.

Predictions have been made over the past decade that stratospheric O_3 will change due to increasing levels of CFCs, and that the circulation of the stratosphere may be altered in response to changes in climate induced by greenhouse gases. Recent detection of the Antarctic ozone hole has dramatized the ability of the atmosphere to change rapidly in response to perturbations. There are currently underway many theoretical studies of the impact of the ozone hole on stratospheric circulation, O_3 fluxes, and the mean chemistry of the stratosphere (e.g., N_2O losses). As discussed above, there are also indications of a declining trend in Northern Hemisphere O_3 not associated with the Antarctic hole. In summary, we expect stratospheric O_3 to change in the next few decades, which will lead to alterations in the lifetimes of the long-lived greenhouse gases and will also perturb tropospheric chemistry through the supply of O_3 and through the increase in solar ultraviolet light available to generate OH.

CONCLUSION

Anthropogenic emissions of both long-lived greenhouse gases and short-lived highly reactive species are altering the composition of the atmosphere. The concentrations of CO_2 and CH_4 have increased dramatically since the preindustrial era, and CFCs have been introduced into the atmosphere for the first time. As a result of the rapid pace of human-induced change, neither atmospheric composition nor climate is currently in equilibrium. Thus, significant global change can be anticipated over the coming decades, no matter what course is taken in the future. The rate and magnitude of change, however, are subject to human control, which serves as the motivation for this report.

TABLE 2-2

Trace Gas Data

CO_2 CARBON DIOXIDE	10^{12} kg C
Atmospheric Burden	720
348.4±0.2 ppm in 1987 Not photochemically active	
Annual Trend	2.3
1.15 ppm/yr (0.3%/yr) since 1984	
Annual Sources	6-7
1. Fossil fuel combustion 4.5%/yr since 1984	5.4
2. Land use Modification	0.4 - 2.6
3. Biosphere -- climate feedback Enhanced aerobic decomposition of detrital material due to more favorable climate	?
Annual Sinks	~ 2.5
1. Ocean Ocean's capacity to absorb CO_2 will be altered by changes in temperature, salinity as wells a biological activity of ocean.	~ 2.5
2. Biosphere Enhanced photosynthetic uptake of CO_2 due to more favorable climate and/or due to CO_2 fertilization	?

TABLE 2-2 (Continued)

CH_4 METHANE	10^9 kg CH_4
Atmospheric Burden	
1675 ppb in 1987 Lifetime: 5 - 10 years	4600 - 4800
Annual Trend	
14 - 16 ppb/yr (0.8-1%/yr)	40 - 46
Annual Sources	500 ± 100
1. Fossil fuel	
Coal mining	15 - 45
Natural gas drilling, venting, and transmission loss	25 - 50
2. Biomass burning	50 - 100
3. Natural wetlands	100 - 200
4. Rice Paddies	60 - 170
5. Animals -- mainly ruminants	65 - 100
6. Termites Population unknown	10 - 100
7. Oceans and freshwater lakes	5 - 45
8. Landfills	30 - 70
9. Methane hydrate destabilization	0 - 100 (future)
Annual Sinks	495 ± 145
1. OH destruction	495 ± 145
2. Dry soils absorption by methane - oxidizing bacteria in dry soils	?

TABLE 2-2 (Continued)

N_2O NITROUS OXIDE	10^9 kg N
Atmospheric Burden	1500
340 ppb in 1986 Lifetime: 100 - 175 years	
Annual Trend	3.5 ± 0.5
0.7 ± 0.1 ppb/yr 0.2%/yr	
Annual Sources	14 ± 3 (inferred)
1. Combustion of coal and oil	1 - 3
2. Land use modification	
Biomass burning	1 - 2
Forest clearings	?
3. Fertilized agricultural lands	0.2 - 2.4
4. Contaminated aquifers	0.8 - 1.7
5. Tropical and subtropical forests and woodlands	6 ± 3
6. Boreal and temperate forests	0.1 - 0.5
7. Grasslands	<0.1
8. Oceans	2 ± 1
Annual Sinks	
Stratospheric photolysis and reaction with $O(^1D)$	10.5 ± 3

TABLE 2-2 (Continued)

NO_x NITROGEN OXIDES	10^9 kg N
$NO_x = \underset{\text{nitric oxide}}{NO} + \underset{\text{nitrogen dioxide}}{NO_2}$	
$NO_y = NO_x + HNO_2 + HNO_3 + HO_2NO_2 + NO_3 + 2N_2O_5$ + PAN + Particulate Nitrate	
Atmospheric Burden -- large variability; lifetime 1-2 days in summer	?
Marine air 4 ppt (NO)	
Continental air	
non-urban sites 2-12 ppb	
U.S. & European cities 70 - 150 ppb	
(100 ppt = 240 x 10^9 kg N)	
Annual Trend	?
Annual Sources -- Spatially and temporally concentrated sources	25 - 99
1. Combustion of coal, oil and gas	14 - 28
2. Biomass burning	4 - 24
3. Lightning	2 - 20
4. Oxidation of ammonia	1 - 10
5. Emission from soils (mostly NO)	4 - 16
6. Input from stratosphere (by reaction of $O(^1D)$ with N_2O)	~ 0.5
Sinks	
1. Wet deposition (precipitation scavenging)	24 - 64
ocean	4 - 12
continents	8 - 30
2. Dry deposition	12 - 22

TABLE 2-2 (Continued)

CO CARBON MONOXIDE	10^9 kg CO
Atmospheric Burden	430
~ 90 ppb (150 - 200 ppb Northern Hemisphere, 75 ppb Southern Hemisphere)	
Lifetime: 0.4 year	
Annual Trend	4
1 - 2%/yr Northern Hemisphere 0 - 1%/yr Southern Hemisphere	
Annual Sources	1500 - 4000
1. Fossil fuel combustion 50% for automobiles residential use of coal industrial activities, e.g., steel production	400 - 1000
2. Oxidation of anthropogenic hydrocarbons 45% emissions from automobiles 40% evaporation of fuels and solvents	0 - 180
3. Biomass burning	
Wood used as fuel	25 - 150
Forest wildfires	10 - 50
Forest clearing	200 - 800
Savanna burning	100 - 400
4. CH_4 oxidation	400 - 1000
5. Oxidation of natural hydrocarbons (isoprenes and terpenes)	280 - 1200
6. Emission by plants	50 - 200
7. Ocean	20 - 80
Annual Sinks	3420
1. Soil uptake	250
2. Photochemistry	3170

TABLE 2-2 (Continued)

Chemical Formula	Name	Concentration (pptv)	Annual Trend	Global Prod. (10^6 kg)	Sources	Sinks	Lifetime (years)
$CFCl_3$	CFC-11	226 (1986)	+4%	350 (1986) (CMA rep. co.'s only)	Rigid and flexible foam; Aerosol propellant	Removal in stratosphere	75^{+32}_{-17} (65)
CF_2Cl_2	CFC-12	392 (1986)	+4%	480 (1986) (CMA reporting co.'s plus USSR estimate)	Refrigerant; Rigid and flexible foam; Aerosol propellant	Removal in stratosphere	111^{+222}_{-46} (120)
$CHClF_2$	HCFC-22	~100 (1986)	~+7% (1986)	206 (1984) 163 (1981) 102 (1977)	Refrigerant; production of Teflon polymers (fluoropolymers)	Removal in stratosphere	20
CCl_2FC-ClF_2 (C_2Cl_3F3)	CFC-113	30-70 (1986) (calibration uncertain)	+11%	138-141 (1984) 91 (1979) 79 (1978) 70 (1977)	Electronics solvent	Removal in stratosphere	90
CH_3CCl_3	Methyl-chloroform	125 (1986)	7%	~580 (1985)	Industrial degreasing of metallic or metaplastic pieces; cold cleaning Solvent of adhesives, varnishes and paints	Removal by OH in troposphere	5.5 - 10

TABLE 2-2 (Continued)

Chemical Formula	Name	Concentration (pptv)	Annual Trend	Global Prod. (10^6 kg)	Sources	Sinks	Lifetime (years)
CCl_4	Carbon Tetrachloride	75-100 (1986) (calibration uncertain)	+1%	~1000 (1985) atmospheric emissions 80-110	Chemical intermediate in CFC-11, 12 production Declining use as: Solvent in chemical & pharmaceutical processes and as grain fumigant	Stratospheric photolysis, perhaps some hydrolysis in ocean	~50
CH_3Cl	Methyl chloride	~600 (1986)		(2000-5000 total, based on OH); 500 industrial	Burning Vegetation Release from oceans Industrial	Troposphere	~1.5
$CBrClF_2$	Halon-1211 (BCF)	~2 (1986) (calibration uncertain)	>10% (1985)	~5 (est. from obs. of atm. increase)	High-tech fire extinguisher (portable)	Photolysis in stratosphere and upper troposphere	25
$CBrF_3$ (CF_3Br)	Halon-1301	~2 (1986) (calibration uncertain)	>10%	7-8? (1984)	Fire extinguisher when CO_2, H_2O are unacceptable (Refrigerant)	Photolysis in stratosphere	110
CF_3Cl	CFC-13	~3.4(1980)	~5% (avg. of 5 sites)	----		Removal in stratosphere	400
$CClF_2CClF_2$	CFC-114	-----		13-14 (1985) Constant at 13 from 1979-84	Aerosol propellant Refrigerant; Production of CFC-115	Removal in stratosphere	180

TABLE 2-2 (Continued)

Chemical Formula	Name	Concentration (pptv)	Annual Trend	Global Prod. (10^6 kg)	Sources	Sinks	Lifetime (years)
C_2F_5Cl	CFC-115	~4 (1980)				Removal in stratosphere	380
C_2F_6	CFC-116	~4 (1980)	----			Removal in stratosphere	>500
CH_3Br	Methyl bromide	9 (1984)	small	?	Leaded motor fuel; Fumigation 50% natural (anthropogenic sources prob. declining)		~3 (2.3)
$CHBr_3$	Bromoform	~2 (1984)	?	?	Mainly natural		?
$C_2H_4Br_2$	Ethylene dibromide (EDB)	~1 (1984)	?	?	Evaporation of leaded gasoline; Fumigation; anthropogenic sources probably declining		~1
CH_2Br_2 $CHBrCl$ CH_2BrCl_2		1-4 for group; 3.2 (1984)			May well be oceans		
CH_3I	Methyl iodide	~1 (1981)	----				.02

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INTRODUCTION

The increasing concentrations of greenhouse gases documented in the last chapter are expected to alter significantly the Earth's climate in the coming decades. The magnitude and timing of actual climatic change will be determined by future emissions (Chapter V), by changes in other climatic forcings, and by the sensitivity of the climate system to perturbations. Weather and climate (the time-average of weather) are determined by complex interactions between the atmosphere, land surface, snow, sea ice, and oceans, involving radiative and convective exchange of energy within and among these components. As is readily apparent, this system exhibits considerable variability from day to day, month to month, and year to year.

Systematic diurnal (day-night) and seasonal variations are driven by changes in the distribution and amount of solar energy reaching the top of the Earth's atmosphere as the Earth rotates on its axis and orbits around the sun. Changes in the amount of energy emitted by the sun, changes in the atmospheric composition (due to volcanic eruptions and human input of aerosols and greenhouse gases), and changes in the earth's surface (such as deforestation) can also affect the earth's energy balance. Such factors are considered "external forcings" because they do not depend on the state of the climate system itself.

In contrast, much of the day to day and year to year variation results from the internal dynamics of the climate system. For example, the polar front may be unusually far south in North America during a given year, producing colder than normal weather in the northern Great Plains, but there can be warmer than average weather somewhere else, leaving the global average more or less unchanged. Similarly, upwelling of cold water off the Pacific Coast of South America may fail for several years. This irregularly recurring event, referred to as El Niño, leads to various regional weather anomalies, impacts like the collapse of the Peruvian anchovy fishery, and warmer global temperature sensitivity to anthropogenic emissions of greenhouse gases is greater than the possibility of such feedbacks decreasing this sensitivity.

- Uncertainties about ocean circulation and heat uptake, and about future internal climate oscillations and volcanic eruptions, make it difficult to predict the time-dependent response of climate to changes in greenhouse gas concentrations. Because the oceans delay the full global warming that would be associated with any increase in greenhouse gases, significant climatic change could continue for decades after the composition of the atmosphere were stabilized. The Earth already is committed to a total warming of about 0.7-1.5°C (assuming that the climate sensitivity to doubling CO_2 is 2-4°C). The Earth has warmed by 0.3-0.7°C during the last century, which is consistent with expectations given the uncertain delay caused by ocean heat uptake.

FINDINGS

- Climate exhibits natural variability on all time scales, from years to millions of years. This variability is caused by a combination of changes in external factors, such as solar output, and internal dynamics and feedbacks, such as the redistribution of heat between the atmosphere and the oceans.

- The ultimate warming that can be expected for a given increase in greenhouse gas concentrations is uncertain due to our inadequate understanding of the feedback processes of the climate system. For the benchmark case of doubling carbon dioxide concentrations, the National Academy of Sciences has estimated that the equilibrium increase in global average temperature would most likely be in the range of 1.5-4.5°C; recent analyses suggest that the warming could be as much as 5.5°C; a reasonable central uncertainty range is 2-4°C.

- A variety of geophysical and biogenic feedbacks exist that have generally been ignored in quantifying the temperature change that could occur for any given initial increase in greenhouse gases. In particular, the potential of future global warming to increase emissions of carbon from northern latitude reservoirs in the form of both methane and carbon dioxide, to alter uptake of CO_2 by oceans, and a variety of other temperature dependent phenomena indicate that the true sensitivity of the Earth's climate system to increased greenhouse gases could exceed 5.5°C for an initial doubling of CO_2. While there are biogenic and geochemical feedbacks that could decrease greenhouse gas concentrations -- enhanced photosynthesis due to higher CO_2, for example -- it appears that the risk of all biogenic and geochemical feedbacks raising the Earth's true

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temperatures. In this case there is a temporary net release of heat from the ocean to the atmosphere, which is usually followed by a reversal, sometimes referred to as La Niña (Kerr, 1988). Such random variations of the atmospheric and oceanic circulation can produce anomalous redistributions of energy in the climate system resulting in random climate variations, with amplitudes and time scales which may be comparable to climate changes expected from past increases in greenhouse gases (Lorenz, 1968; Hasselmann, 1976; Robock, 1978; Hansen et al., 1988).

In order to determine precisely the potential effects of the input of greenhouse gases on future climate, it would be necessary not only to be able to understand all the physics of the climate system and the effects of each potential cause of climate change, but also to be able to predict the future changes of these forcings. If we could do this, we could explain past climate change and separate the effects of greenhouse gases from the other factors that have acted during the past 100 years for which we have instrumental temperature records. We could also use theoretical climate models to calculate the future size and timing of climate changes due to greenhouse gases. Since our measurements of past climate are incomplete, our understanding of the climate system is incomplete, and some (not well known) portion of climate change is random and unpredictable, we can only estimate the impact of greenhouse gas buildup within a broad range of uncertainty.

In this chapter we discuss in brief the magnitude and rate of past changes in climate and examine the various factors influencing climate in order to place the potential warming due to increasing greenhouse gas concentrations in context. Feedback mechanisms that can amplify or lessen imposed climate changes are discussed next. The overall sensitivity of climate to changes in forcing is then considered, followed by a discussion of the time-dependent response of the Earth system. The focus is on global temperature as an indicator for the magnitude of climatic change. Regional climate and the potential impacts of climatic change are not discussed here, but are considered in the companion report *Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989).

CLIMATIC CHANGE IN CONTEXT

The most detailed information on climate is, of course, from the modern instrumental record, but even this data set is quite sparse in the Southern Hemisphere and over the oceans. Wigley et al. (1986) reviewed a number of recent analyses, noting that independent groups (including Hansen et al., 1981 and Vinnikov et al., 1980; more recent publications are Hansen and Lebedeff, 1988 and Vinnikov et al., 1987), necessarily relying on the same basic data sources, but using different data selection and averaging approaches, have obtained very similar results. Given the various uncertainties due to factors such as poor spatial coverage in some regions, changes in the number and location of stations, growth of urban heat islands, and changes in instrumentation, Wigley et al. conclude that the warming since 1900 has been in the range of 0.3-0.7°C. The most complete and up-to-date global surface air temperature record available (Jones et al., 1988) is displayed in Figure 3-1a, which shows a global warming of about 0.3°C from 1900 to 1940, a cooling of about 0.1°C from 1940 to 1975 and a warming of about 0.2°C from 1975 to 1987. The four warmest years in the record occurred during the 1980s: 1980, 1981, 1983, and 1987. The overall warming is similar in the land air temperature record of the Northern and Southern Hemispheres (Figures 3-1b,c), though the long-term trend is steadier in the Southern Hemisphere where the 1940-1975 cooling is less evident. While the gradual warming seen in Figure 3-1 during the past century is not inconsistent with the increasing greenhouse gases during this period (Chapter II), the large interannual variations and the relatively flat curve from 1940 to 1975 show that there are also other important causes of climate change. The differences between the two hemispheres also show that there are regional differences in the climate response to a global forcing (greenhouse gases), that important other forcings (such as large volcanic eruptions) are not global in their effects, or that internal climate variations produce regional differences. Because of past and potential future emissions of greenhouse gases (see below and Chapter V), climate changes during the next century may be larger than the variations shown for the past 100 years.

FIGURE 3-1

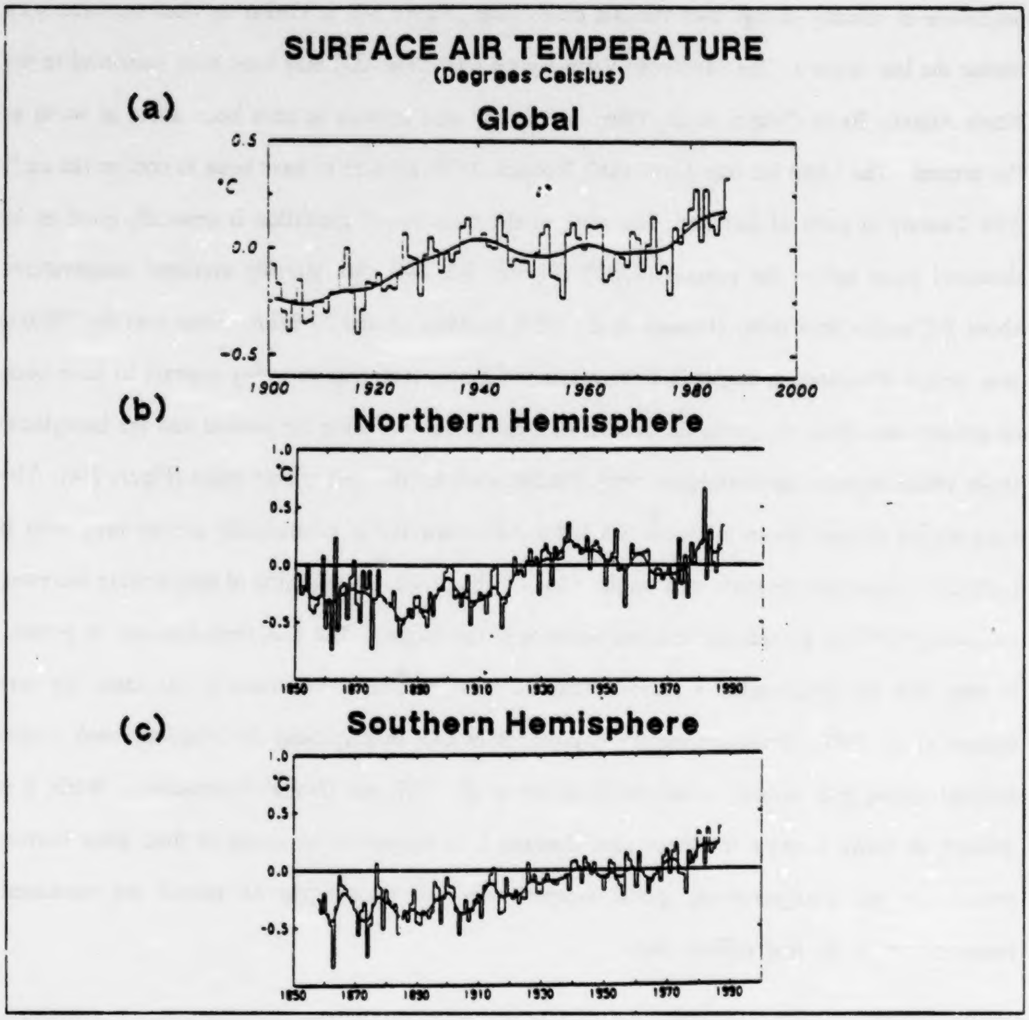


Figure 3-1. (a) Global surface air temperature, 1901-1987. This record incorporates measurements made both over land and from ships. The smooth curve shows 10-year Gaussian filtered values. The gradual warming during this period is not inconsistent with the increasing greenhouse gases during this period, but the large interannual variations and the relatively flat curve from 1940 to 1975 show that there are also other important causes of climate change. (Source: Jones et al., 1988.)

(b,c) Land surface air temperatures, 1851-1987 for the Northern Hemisphere (NH) and 1857-1987 for the Southern Hemisphere (SH). Note the larger interannual variability before 1900, when data coverage was much more sparse. (Source: Jones, 1988.)

Recent climate variations are put in a longer-term perspective in Figures 3-2 through 3-4. The amplitude of climatic change over the last millennium (Figure 3-2) is similar to what has been seen during the last century. The Medieval Warm Epoch (800-1200 AD) may have been restricted to the North Atlantic Basin (Wigley et al., 1986), and in any case appears to have been about as warm as the present. The Little Ice Age (1430-1850; Robock, 1979) appears to have been as cool as the early 20th Century in parts of Europe. The peak of the most recent glaciation is generally given as 18 thousand years before the present (kyBP) (Figures 3-3, 3-4) with globally averaged temperatures about 5°C cooler than today (Hansen et al., 1984) between 15 and 20 kyBP. Even over the 700,000 year period illustrated in Figure 3-4 the maximum global temperature swing appears to have been no greater than about 5°C, with the periods of greatest warmth being the present and the interglacial peaks which occurred approximately every 100,000 years for the past million years (Figure 3-4). The temperature change shown in Figure 3-3 is for Antarctica and is substantially greater than what is believed to represent the globe as a whole. (Such high-latitude amplification of temperature increases can be expected for greenhouse-induced warming in the future). The CO_2 variations are, in general, in step with the temperature variations deduced from deuterium variations in the same ice core (Jouzel et al., 1987), demonstrating the importance of CO_2 in amplifying the relatively weak orbital forcings during past climate variations (Genthon et al., 1987; see Orbital Parameters). While it is difficult to assign a cause for these past changes, it is reasonable to conclude that, given current greenhouse gas concentrations, global temperatures will soon equal or exceed the maximum temperatures of the past million years.

CLIMATE FORCINGS

The patterns of climate variations discussed in the last section are the result of a combination of external forcings, internal feedbacks, and unforced internal fluctuations. The strictly external forcings are changes in solar output and variations in the Earth's orbital parameters, while changes

FIGURE 3-2

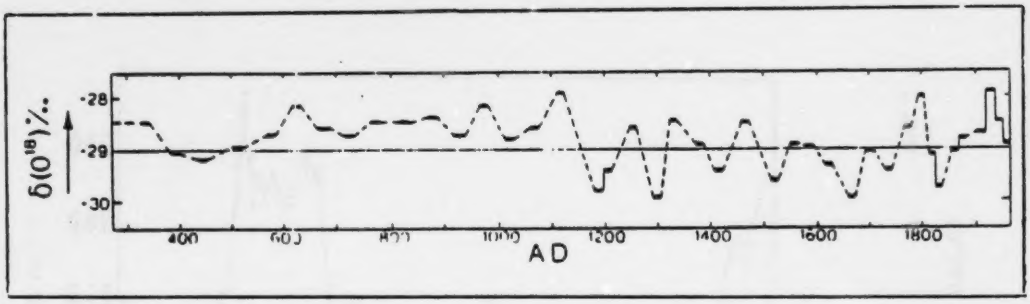


Figure 3-2. Oxygen isotope (δ^{18}O) variations from ice cores in Greenland. This is an index of Northern Hemisphere temperature, with the maximum range equal to about 1°C. (Source: record of Dansgaard as given by Lamb, 1977.)

FIGURE 3-3

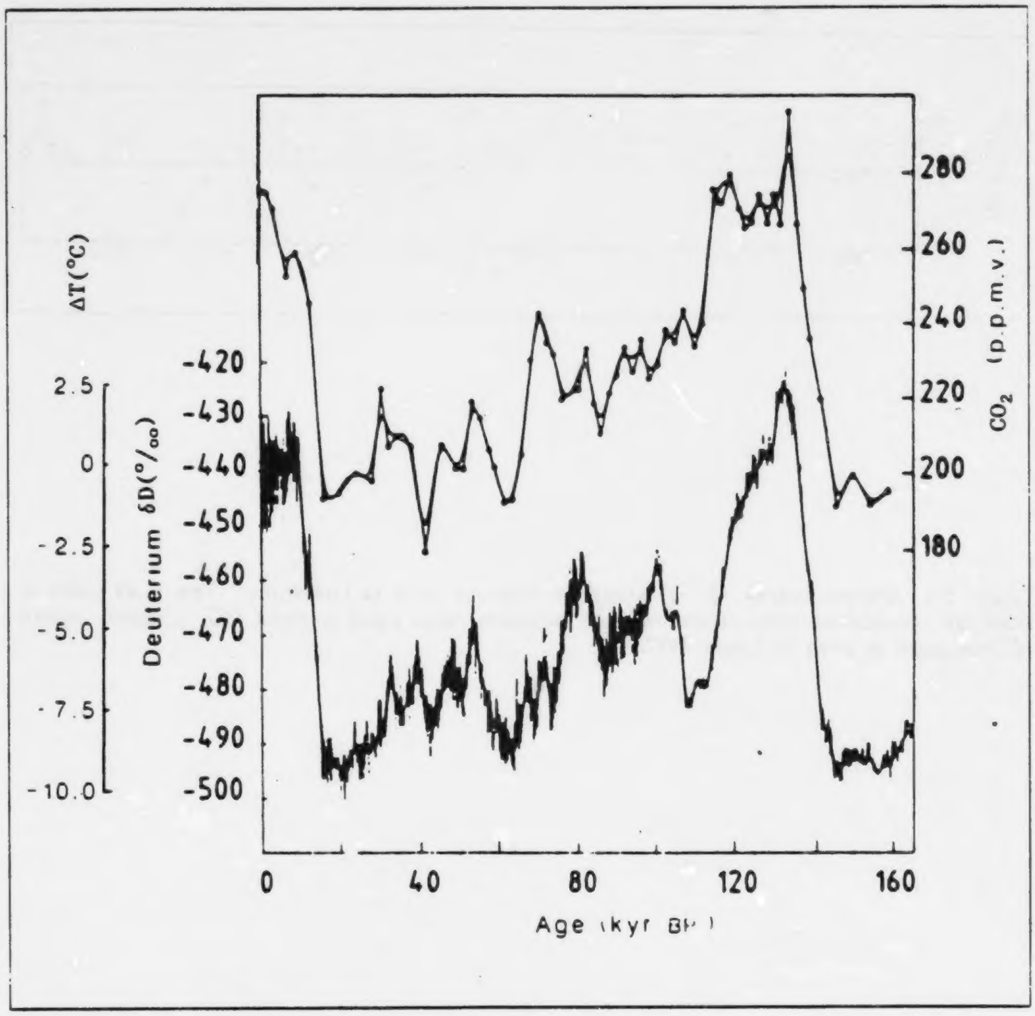


Figure 3-3. Carbon dioxide levels and temperatures over the last 160,000 years from Vostok 5 Ice Core in Antarctica. The temperature scale is for Antarctica; the corresponding amplitude of global temperatures swings is thought to be about 5°C. (Source: Barnola et al., 1987.)

FIGURE 3-4

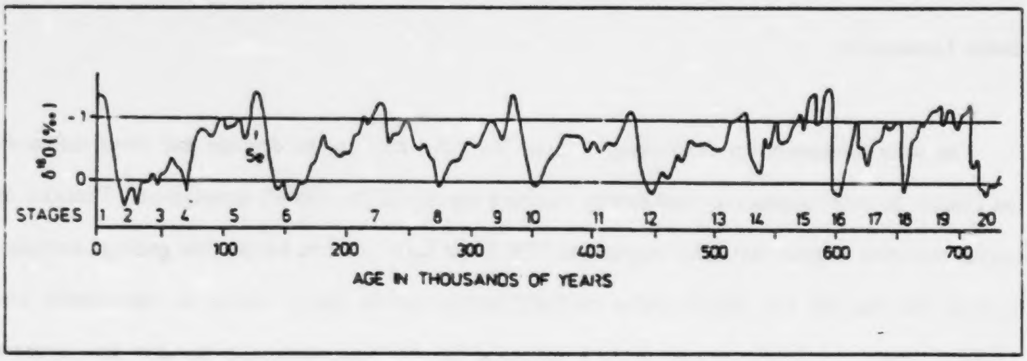


Figure 3-4. Composite $\delta^{18}O$ record of Emiliani (1978) as given by Berger (1982). This comes from deep sea sediment cores and is an index of global temperature, with the temperature range from stage 1 (present) to stage 2 (18,000 years ago) equal to about 5°C.

in aerosols and greenhouse gas concentrations may be viewed as external forcings or internal feedbacks, depending on the time scale and processes considered. The sensitivity of the climate system is determined by the feedbacks that modify the extent to which climate must change to restore the overall energy balance of the Earth as external forcings change.

Solar Luminosity

The solar luminosity (or total energy output from the sun) has an obvious and direct influence on climate by determining the total energy reaching the top of the Earth's atmosphere. Theories of stellar evolution suggest that solar output was 25% lower early in Earth history, but geologic evidence and the fact that life was able to evolve on Earth shows that the Earth was not an inhospitable ice-covered planet. An important part of the explanation for this "faint young sun paradox" now appears to be that the CO_2 content of the atmosphere was many times higher than it is at present. The enhanced greenhouse effect from CO_2 was probably the main factor in counteracting the lower solar luminosity (see below). Geochemical models suggest that over millions of years CO_2 has acted as an internal feedback that has kept the Earth's climate in a habitable range (Walker et. al., 1981; Berner and Lasaga, 1988; Figure 3-2b).

Solar luminosity also varies by small but significant amounts over shorter time periods. Various attempts have been made to explain past climate variations by assuming a link between solar luminosity and observed parameters, such as sunspot activity, solar diameter, and the umbral-penumbral ratio (Wigley et al., 1986). Unfortunately, measurements with sufficient precision to detect solar luminosity changes have only been available since 1979 -- too short a time period to be able to definitively confirm or refute the proposed relationships. These measurements show a decline in solar luminosity between 1980 and 1986; whereas the most recent data show a reversal of this trend (Willson and Hudson 1988; Willson et al., 1986). The luminosity data are positively correlated with sunspot number and suggest an 11-year cycle with an amplitude of 0.04% or 0.1 W/m^2 at the top of the atmosphere (Willson and Hudson, 1988).

Orbital Parameters

Cyclic changes in Earth orbital characteristics are now widely accepted as the dominant trigger behind the glacial/interglacial variations evident in Figure 3-3 and extending back to at least 1.7 million years before present (e.g., Wigley et al., 1986; COHMAP, 1988). While causing only small changes in the total radiation received by the Earth, the orbital changes (known as the Milankovitch cycles) significantly alter the latitudinal and seasonal distribution of insolation. For example, Northern Hemisphere summer insolation was about 8% greater 9 kyBP than it is now, but winter insolation was 8% lower. Changes of this type, in combination with internal feedbacks as discussed below, are presumed to have determined the pattern of glaciations and deglaciations revealed in the geologic record. Attempts have been made to compare model predictions with paleoclimatic data. There has been reasonably good agreement between the two, given specified ice sheet extent and sea surface temperatures (COHMAP, 1988; Hansen et al., 1984). To the extent that the Milankovitch explanation of ice ages is correct, one would expect the Earth to be heading toward a new ice age over the next 5000 years, but the very gradual changes in orbital forcings expected in this period will be overwhelmed if current trends in greenhouse gas concentrations continue (Wigley et al., 1986).

Volcanoes

Large volcanoes can significantly increase the stratospheric aerosol concentration, increasing the planetary albedo and reducing surface temperatures by several tenths of degree for several years (Hansen et al., 1978, 1988; Robock, 1978, 1979, 1981, 1984). Because of the thermal inertia of the climate system, discussed below, volcanoes can even be responsible for climate changes over decades, and in fact the warming shown in Figure 3-1 from 1920 to 1940 can be attributed to a period with very few volcanic eruptions (Robock, 1979). Since large eruptions occur fairly frequently and cannot now be predicted, this component of climate change will have to be considered when searching past climate for a greenhouse signal and when projecting future climate change.

Surface Properties

The Earth's radiative balance can also be changed by variations of surface properties. While interactions with the ocean, which covers 70% of the Earth's surface, are considered internal to the climate system and are discussed below, land surfaces also exert a strong influence on the climate. Human activities, such as deforestation, not only provide a source of CO_2 and CH_4 to the atmosphere, but also change the surface albedo and moisture flux into the atmosphere. Detailed land surface models, incorporating the effects of plants, are now being developed and incorporated into GCM studies of climate change (Dickinson, 1984; Sellers et al., 1986).

The Role of Greenhouse Gases

The greenhouse effect does not increase the total energy received by the Earth, but it does alter the distribution of energy in the climate system by increasing the absorption of infrared (IR) radiation by the atmosphere. If the Earth had no atmosphere, its surface temperature would be strictly determined by the balance between solar radiation absorbed at the surface and emitted IR. The amount of IR emitted by any body is proportional to the fourth power of its absolute temperature, so that an increase in absorbed solar radiation (due to increased solar luminosity or decreased albedo, for example) would be balanced by a small increase in the surface temperature, increasing IR emissions until they are again equal to the absorbed solar radiation. The role of greenhouse gases can be understood by thinking about the atmosphere as a thin layer that absorbs some fraction of the IR emitted by the surface (analogous to the glass in a greenhouse). The energy absorbed by the atmosphere is then remitted in all directions, and the downward half of this energy flux warms the surface (Figure 3-5). Higher concentrations of greenhouse gases increase the IR absorption in the atmosphere, raising surface temperatures.

Changes in the atmosphere's radiative properties can result from external perturbations (such as anthropogenic emissions of CO_2) or from internal adjustments to climatic change. The amount of water vapor, the dominant greenhouse gas, is directly determined by climate and contributes the largest positive feedback to climatic change (Hansen et al., 1984; Dickinson, 1986). Similarly, clouds are an internal part of the climate system that strongly influence the Earth's radiative balance (Ramanathan et al., 1989). Changes in the concentrations of other greenhouse gases may be imposed by human activity or may result from changes in their sources and sinks induced by climatic change. Such feedbacks are discussed below.

Internal Variations

As discussed in the introduction, even with no changes in external forcings, climate still exhibits variations due to internal rearrangements of energy within the atmosphere and between the atmosphere and the ocean. The total amplitude and time scales of these internal stochastic climate variations are not well known; these variations therefore pose an additional difficulty in interpreting the past record and projecting the level of future climate change.

PHYSICAL CLIMATE FEEDBACKS

Any imposed imbalance in the Earth's radiative budget, such as discussed above, will be translated into a changed climate through feedback mechanisms which can act to amplify or decrease

FIGURE 3-5

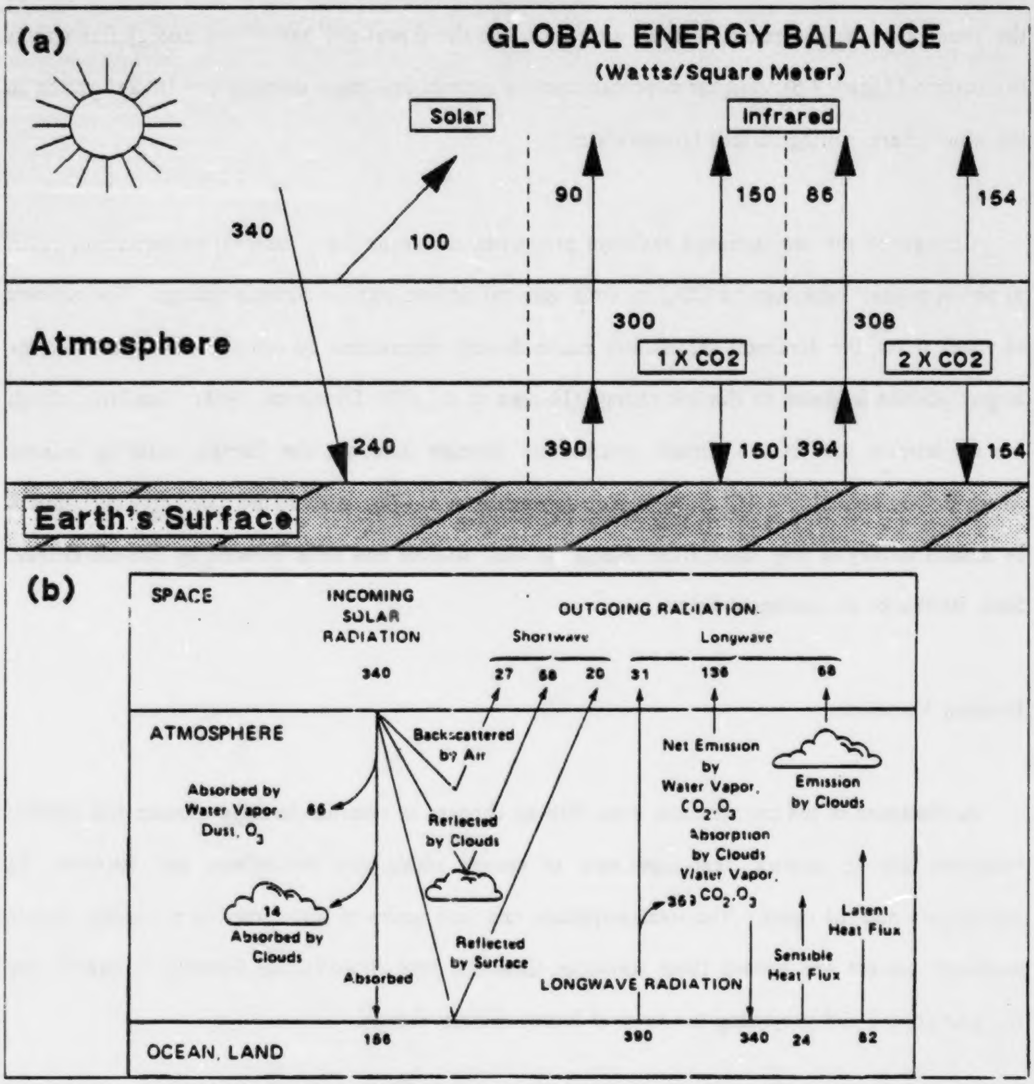

(a)
GLOBAL ENERGY BALANCE
(Watts/Square Meter)
Solar
Infrared
340
100
90
150
86
154
Atmosphere
300
308
1 X CO2
2 X CO2
240
390
150
394
154
Earth's Surface
(b)
SPACE
INCOMING SOLAR RADIATION
OUTGOING RADIATION
Shortwave
Longwave
340
27
68
20
31
136
68
ATMOSPHERE
Backscattered by Air
Absorbed by Water Vapor, Dust, O3
66
Reflected by Clouds
Net Emission by Water Vapor, CO2, O3
Emission by Clouds
Absorption by Clouds Water Vapor, CO2, O3
363
14
Absorbed by Clouds
Reflected by Surface
Absorbed
LONGWAVE RADIATION
Sensible Heat Flux
Latent Heat Flux
OCEAN, LAND
166
390
340
24
82

Figure 3-5. (a) Highly simplified schematic of the global energy balance illustrating the mechanism by which increased greenhouse gas concentrations warm the Earth's surface. The atmosphere is treated as a thin layer that does not absorb solar radiation; the role of convective and latent heat transfer is also neglected. Doubling the concentration of CO_2 increases the absorption and emission of infrared radiation by the atmosphere, increasing the total energy absorbed at the surface. In the equilibrium depicted, total emissions to space remain unchanged.

(b) A more realistic schematic of the global energy balance for current conditions. (Source: adapted from MacCracken, 1985.)

the initial imposed forcing. In this section, several of these mechanisms which are internal to the physical climate system are discussed. In the next section, several recently quantified mechanisms involving the planet's biology and chemistry are described.

By no means do we understand or even know about all the mechanisms involved in climate feedbacks. Figure 3-6 shows some of the physical climate feedbacks involved in changing surface temperature. Current state-of-the-art climate models attempt to incorporate most of the physical feedbacks that have been identified, but are forced, for example, to provide a very crude treatment for one of the most important -- changes in clouds -- because of inadequate understanding of cloud physics and because of the small spatial scale on which clouds form compared to the resolution of climate models.

Water Vapor - Greenhouse

When the climate warms, the atmosphere can hold more water vapor. This enhances the warming because it increases the greenhouse effect from water vapor, producing still more evaporation from the warmed surface. This positive feedback acts to approximately double imposed forcings.

Snow and Ice

When climate warms, snow and ice cover are reduced, exposing land or ocean with a lower albedo than the snow or ice. In addition, the albedo of the remaining snow and ice is reduced due to meltwater puddles and debris on the surface. This acts to absorb more energy at the surface, further enhancing the warming. This albedo feedback was originally thought to be the dominant positive feedback effect of snow and ice, but we now understand that the thermal inertia feedback

FIGURE 3-6

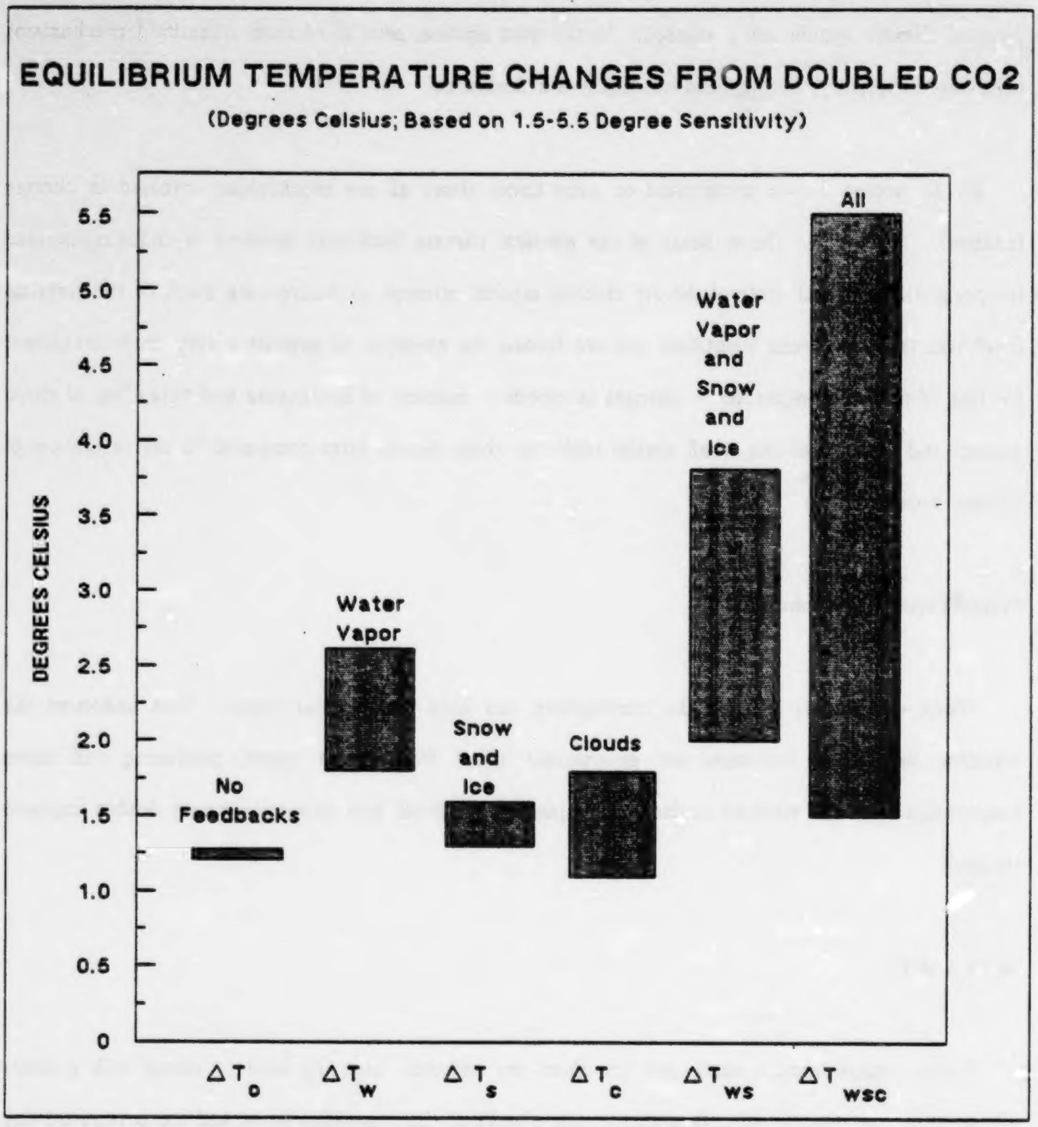


Figure 3-6. Equilibrium temperature changes from doubling CO_2 (ΔT_{2x}) inferred from a review of the strength of individual feedback processes in various climate models. ΔT_0 is the temperature increase expected from doubling CO_2 with no feedbacks. The subscripts w, s, and c, refer to feedbacks due to water vapor and lapse rate, sea ice and surface albedo, and clouds, respectively. Each bar shows the estimated two-standard deviation range of equilibrium global warming with the indicated feedbacks included. (Source: adapted from Dickinson, 1986.)

of sea ice plays a much more important role (Manabe and Stouffer, 1980; Robock, 1983). The albedo feedback requires that the sun be shining, and since the maximum ice and snow extent is in the winter, it plays a small role in influencing the albedo except in the spring, when the snow and ice are present along with high insolation.

The thermal inertia feedback acts to increase the thermal inertia of the oceans when climate warms by melting sea ice, reducing its insulating effect and increasing the transfer of heat from the ocean to the atmosphere at high latitudes. This acts to reduce the seasonal cycle of surface temperature and is the prime reason for the enhancement of imposed climate change in the polar regions in the winter (Robock, 1983). If sea ice retained its current seasonal cycle, there would be no preferential latitude or time of year for climate change.

Clouds

Clouds respond directly and immediately to changes in climate and may represent the most important uncertainty in determining the sensitivity of the climate system to the buildup of greenhouse gases. Fractional cloud cover, cloud altitude and cloud optical depth can all change when climate changes (Schlesinger, 1985). It has not been possible to calculate the net effect of cloud feedbacks because all these properties of clouds can change simultaneously, because clouds affect long-wave radiation, short-wave radiation, and precipitation (which affects soil moisture and hence albedo, thermal inertia, and moisture flux of land), and because the net effect depends on the location of the cloud (in 3 dimensions), the underlying surface albedo, and the time of day and year of the changes. The current net effect of clouds has only recently been measured (Ramanathan et al., 1989). Current climate models include crude calculations of clouds and have difficulty even reproducing the current cloud distribution.

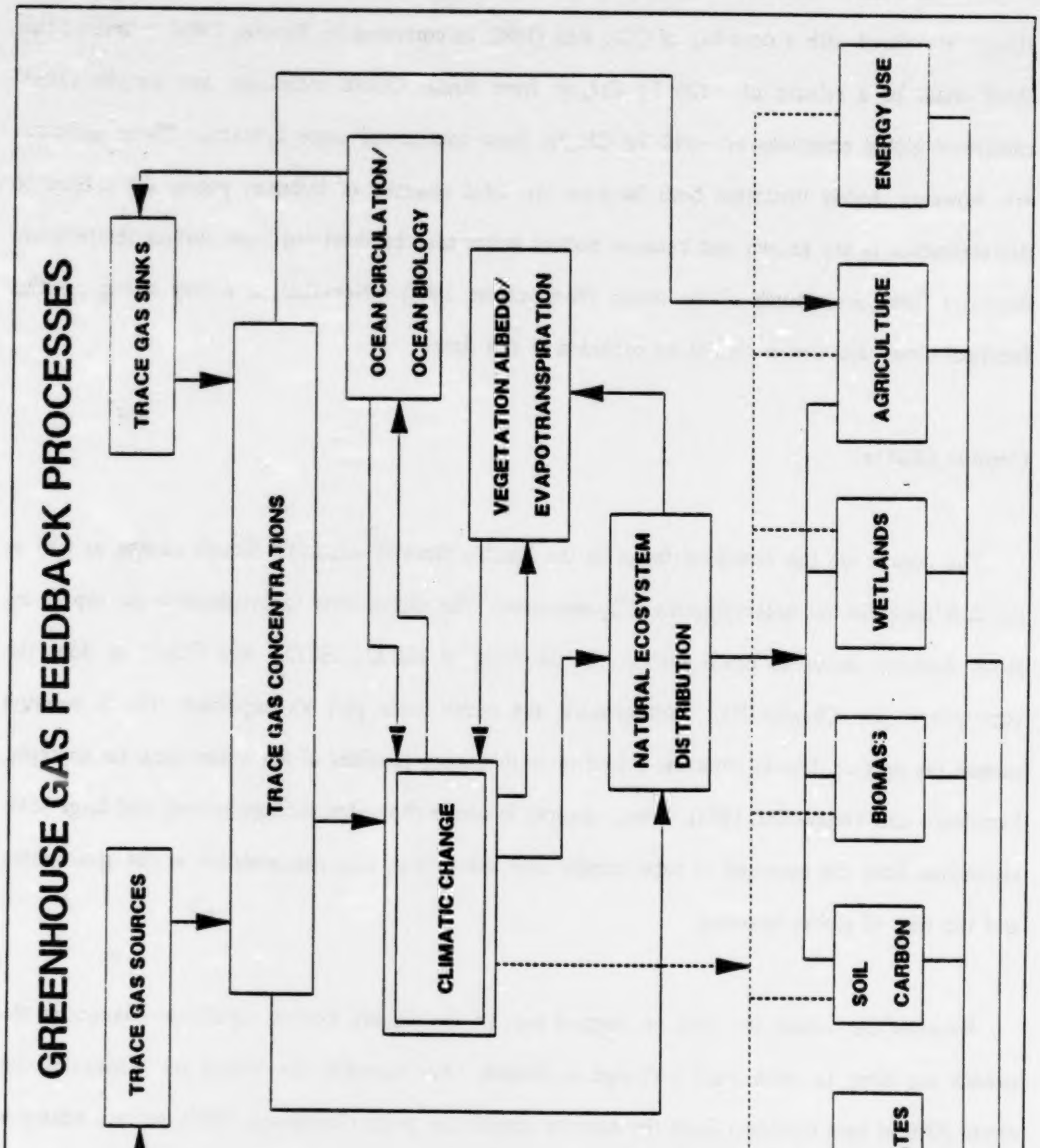
BIOGEOCHEMICAL CLIMATE FEEDBACKS

In addition to the climatic processes discussed above, a number of biogeochemical feedback processes will influence future concentrations of greenhouse gases and climatic change. Increased greenhouse gas concentrations will alter not only the climate, but also biogeochemical processes that affect sources and sinks of radiatively important gases. Climatically important surface properties, such as albedo and evapotranspiration, will also be modified by vegetation changes. The major biogeochemical feedback links, illustrated in Figure 3-7, can be categorized as follows: physical effects of climatic change, changes in marine biology, and changes in terrestrial biology. Potential physical effects of climatic change include release of methane hydrates and changes in ocean chemistry, circulation, and mixing. Changes in marine biology may alter the pumping of carbon dioxide from the ocean surface to deeper waters and the abundance of biogenic cloud condensation nuclei. Potential biological responses on land include changes in surface albedo, increased flux of CO_2 and CH_4 from soil organic matter to the atmosphere due to higher rates of microbial activity, increased sequestering of CO_2 by the biosphere due to CO_2 fertilization, and changes in moisture flux to the atmosphere.

Release of Methane Hydrates

Potentially the most important biogeochemical feedback is the release of CH_4 from near-shore ocean sediments. Methane hydrates are formed when a methane molecule is included within a lattice of water molecules; the ratio can be as small as 1:6, that is, one methane molecule for every six water molecules (Bell, 1982). The hydrate structure is stable under temperature and pressure conditions that are typically found under a water column of a few hundred meters or more in the Arctic and closer to a thousand meters in warmer waters; the region where hydrates are found can start at the sea floor and extend up to a few hundred meters into the sediment, depending on the

FIGURE 3-7


GREENHOUSE GAS FEEDBACK PROCESSES
TRACE GAS SOURCES
TRACE GAS SINKS
TRACE GAS CONCENTRATIONS
CLIMATIC CHANGE
OCEAN CIRCULATION/ OCEAN BIOLOGY
VEGETATION ALBEDO/ EVAPOTRANSPIRATION
NATURAL ECOSYSTEM DISTRIBUTION
ENERGY USE
AGRICULTURE
WETLANDS
BIOMASS
SOIL CARBON
CH4 HYDRATES

geothermal temperature gradient (Kvenvolden and Barnard, 1984). Estimates of the total quantity of CH_4 contained in hydrates range from $2x10^3$ to $5x10^6$ Pg (Kvenvolden, 1988). Given the climatic change associated with a doubling of CO_2, Bell (1982; as corrected by Revelle, 1983) estimated that there could be a release of ~120 Tg CH_4/yr from Arctic Ocean sediments, and Revelle (1983) calculated global emissions of ~640 Tg CH_4/yr from continental slope hydrates. These estimates are, however, highly uncertain both because the total quantity of hydrates potentially subject to destabilization is not known and because bottom water may be insulated from surface temperature increases throughout much of the ocean (Kvenvolden, 1988). Nonetheless, a very strong positive feedback from this source cannot be excluded at this time.

Oceanic Change

The oceans are the dominant factor in the Earth's thermal inertia to climate change as well as the dominant sink for anthropogenic CO_2 emissions. The mixed layer (approximately the top 75 m) alone contains about as much carbon (in the form of H_2CO_3, HCO_3^-, and $CO_3^=$) as does the atmosphere (see Chapter II). Furthermore, the ocean biota play an important role in carrying carbon (as organic debris) from the mixed layer to deeper portions of the ocean (see, for example, Sarmiento and Toggweiler, 1984). Thus, changes in ocean chemistry, biology, mixing, and large-scale circulation have the potential to substantially alter the rate of CO_2 accumulation in the atmosphere and the rate of global warming.

Because the oceans are such an integral part of the climate system, significant changes in the oceans are likely to accompany a change in climate. For example, the oceans are responsible for about 50% of heat transport from the equator toward the poles (Dickinson, 1986), surface mixing is driven by winds, and deep circulation is driven by thermal and salinity gradients. The feedbacks involving the ocean can be divided into three categories: the direct effect of temperature on carbonate chemistry, reduced mixing due to increased stability of the thermocline, and the possibility of large-scale reorganization of ocean circulation and biological activity[1].

Ocean Chemistry

The most straightforward feedback is on ocean carbonate chemistry. As the ocean warms, the solubility of CO_2 decreases and the carbonate equilibrium shifts toward carbonic acid; these effects combine to increase the partial pressure of CO_2 (pCO_2) in the ocean by 4-5%/°C for a fixed alkalinity and total carbon content. Because the total carbon content would only have to decrease by about one-tenth this amount to restore pCO_2 to its previous level, the impact of this feedback is to increase atmospheric CO_2 by about 1%/°C for a typical scenario (Lashof, 1989; Chapter VI).

Ocean Mixing

As heat penetrates from the mixed layer of the ocean into the thermocline the stratification of the ocean will increase and mixing can be expected to decrease, resulting in slower uptake of both CO_2 and heat. This feedback raises the surface temperature that can be expected in any given year for two reasons: First, the atmospheric CO_2 concentration will be higher because the oceans will take up less CO_2. Second, the realized temperature will be closer to the equilibrium temperature due to reduced heat transport into the deep ocean (see the discussion of the transient response below).

---

[1] The thermocline starts at the base of the mixed layer and extends to a depth of about 1000m. It is characterized by a rapid decrease in temperature with increasing depth, which inhibits mixing in the water column because the colder deeper water is denser than the warmer overlying water.

Ocean Biology and Circulation

A more speculative, but potentially more significant, feedback involves the possibility of large-scale changes in the circulation of the atmosphere-ocean system as suggested by Broecker (1987). This possibility is illustrated by the apparently very rapid changes in the CO_2 content of the atmosphere during glacial-interglacial transitions as revealed by ice-core measurements (e.g., Jouzel et al., 1987; Figure 3-2a). Only shifts in carbon cycling in the ocean are thought to be capable of producing such large, rapid, and sustained changes in atmospheric CO_2. A number of papers have attempted to model the changes in ocean circulation and/or biological productivity required to account for the change in pCO_2, emphasizing the importance of high-latitude processes (Kerr, 1988; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984; Knox and McElroy, 1984). Given that continuation of current trends could lead to a climate change during the next century of the same magnitude as that which occurred between glacial and interglacial periods, one must take seriously the possibility of sudden changes in ocean circulation. Should this happen, the oceans could even become a CO_2 source rather than a sink -- significantly accelerating climatic change. Such changes in circulation could also cause abrupt changes in climate, a scenario that conflicts with the general assumption that the warming will be gradual (Broecker, 1987).

A different feedback involving ocean biology has been proposed by Charlson et al. (1987). It is also uncertain, but potentially significant. Dimethyl sulfide (DMS) emitted by marine phytoplankton may act as cloud condensation nuclei in remote marine environments, affecting cloud reflectivity and therefore climate (Charlson et al., 1987; Bates et al., 1987). Climate presumably affects biogenic DMS production but the relationship is complex and poorly understood at this time (Charlson et al., 1987). While this mechanism was originally proposed as a potential negative feedback consistent with the Gaia Hypothesis (Lovelock, 1988; Lovelock and Margulis, 1973), ice-core data indicate that aerosol levels were higher during the last glacial maximum, suggesting that biogenic DMS production may act instead as a positive feedback (Legrand et al., 1988). This is only one possible cloud optical property feedback (discussed above), and the net effect cannot be determined because other cloud properties (amount, elevation) would also change in a complex way.

Changes in Terrestrial Biota

The terrestrial biota interact with climate in a wide variety of important ways (Figure 3-7). The most significant effects on climate may result from large-scale reorganization of terrestrial ecosystems as well as the direct effects of temperature and CO_2 increases on carbon storage.

Vegetation Albedo

Probably the most significant global feedback produced by the terrestrial biota, on a decades-to-centuries time scale is due to changes in surface albedo (reflectivity) as a result of changes in the distribution of terrestrial ecosystems. Changes in moisture flux patterns are probably also important. Cess (1978) argued that vegetation albedo feedback could have played a major role in explaining the glacial-interglacial temperature change. Dickinson and Hanson (1984) reanalyzed this problem and found a much smaller, but still significant effect, i.e., that the planetary albedo was 0.0022 higher at the glacial maximum due to differences in mean annual vegetation albedo. A similar result was obtained by Hansen et al. (1984) using a prescriptive scheme to relate vegetation type to climate in GCM simulations for current and glacial times. (The much larger effect found by Cess was due to differences in the albedo assigned to similar vegetation types for 18 kyBP versus the present [Dickinson and Hanson, 1984].) This feedback may be less important in the future than it was during the last deglaciation because of direct human effects on the surface, such as deforestation, and because the pattern of vegetation change will be different.

is lost as isoprene and terpene (Mooney et al., 1987). Lamb et al. (1987) found that the volume of biogenic NMHC emissions in the United States is greater than anthropogenic emissions by about a factor of two. The ratio for the globe is probably greater. Emissions, at least for isoprene and α-pinene are exponentially related to temperature (Lamb et al., 1987; Mooney et al., 1987). The first-order impact of climatic change, then, would be to increase NMHC emissions, producing a positive feedback through the CO-OH-CH_4 link. The actual impact when changes in ecosystem distribution are considered is uncertain, however, as different species have very different emissions (Lamb et al., 1987).

Summary

Of the feedbacks that will come into play during the next century, the physical climate feedbacks discussed earlier (water vapor, clouds, ice cover, and ice and snow albedo) will almost certainly have the greatest impact. In comparison, the potential individual impacts of the biogeochemical feedbacks discussed here are rather modest. If the physical climate feedbacks approach the strongly positive end of their ranges, then the overall sensitivity of the climate system would be substantially increased by even small additional feedbacks. However, since both the internal and biogeochemical feedbacks are presently so poorly understood, and since other feedbacks may be discovered, the overall equilibrium response of the climate system (discussed below) can only be specified with a fairly wide range.

The perturbations to global biogeochemical cycles reflected in the feedback processes discussed here are of great importance in their own right in addition to whatever warming they may produce. The vegetation albedo feedback, for example, contributed only 0.3°C out of the 3.6°C global cooling in the ice-age analysis of Hansen et al. (1984), but this represented a massive change in terrestrial ecosystems. A better assessment of both the impact of climatic change on biogeochemical cycles and the associated feedbacks is needed. Several aspects of the impact of climatic change on biogeochemical processes are discussed in the companion report *Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989). A quantitative estimate of the impact of some of the feedbacks discussed here is presented in Chapter VI based on incorporating them in the Atmospheric Stabilization Framework developed for this study.

EQUILIBRIUM CLIMATE SENSITIVITY

When any forcing, such as an increase in the concentration of greenhouse gases, is applied to the climate system, the climate will start to change. Since both the imposed forcings and the climatic response are time-dependent, and since the climate system has inertia due to the response times of the ocean, the exact relationship between the timing of the forcings and the timing of the response is complex. In an attempt to simplify the problem of understanding the sensitivity of the climate system to forcings, it has become a standard experiment to ask the question, "What would be the change in global average surface air temperature if the CO_2 concentration in the atmosphere were doubled from the preindustrial level, all other climate forcings were held constant, and the climate became completely adjusted to the new radiative forcing?" This quantity is called the "equilibrium climate sensitivity to doubled CO_2" and is indicated as ΔT_{2X} (see Box 3-1).

The actual path that the climate system would take to approach the equilibrium climate would be determined by the time scales of the forcings and the various elements of the climate system. This is called the "transient response" and is discussed in the next section. Because the climate system response always lags the forcing, there will always be a built-in unrealized warming that will occur in the future, even if no more forcing occurs. Thus, there is certain to be some future climate response to greenhouse gases that were put into the atmosphere in the past, even if no more are put in starting today. Another way of saying this is that societal responses to the greenhouse problem

BOX 3-1. SIMPLIFIED MODELING FRAMEWORK

The concepts discussed in this chapter can be summarized in a simple zero-dimensional or one-box model of climate as discussed by Dickinson (1986):

$$C(d\Delta T/dt) + \lambda\Delta T = \Delta Q \qquad (1)$$

where ΔQ is the climate forcing and could be due to changes in solar output, volcanoes, surface properties, stochastic processes or greenhouse gases (as discussed under Climate Forcings and Feedbacks); ΔT is the change in tropospheric/mixed-layer temperature from the preindustrial equilibrium climate; the factor λ, called the "feedback parameter" by Dickinson, gives the change in upward energy flux resulting from a change in surface temperature, ΔT, and is the net result of all the climate feedbacks (as discussed in the section on Climate Sensitivity); t is time; and C is the effective heat capacity of the Earth, which is determined by the rate of heat uptake by the ocean (C must be a function of time to account for the gradual penetration of heat into an increasing volume of the deep ocean and changing sea ice cover). In equilibrium the first term in (1) is zero, so the equilibrium climate sensitivity is simply given by

$$\Delta T = \Delta Q/\lambda. \qquad (2)$$

For a doubling of CO_2, ΔQ is about 4.3 W/m^2, so the range 1.5-5.5°C of ΔT discussed above corresponds to a range of 2.9-0.8 $W\ m^{-2}\ {}^\circ C^{-1}$ in λ. This conceptual model, with ΔQ calculated from changes in greenhouse gases and C replaced by a diffusive model of the ocean, is incorporated into the Integrating Framework used in the modeling exercises for this report (see Chapter V and Appendix A).

that are undertaken now will be felt for decades in the future, and lack of action now will similarly bequeath climate change to future generations.

Analysis of past climate change, and model calculations of future climate change can both be used to determine ΔT_{2x}. Unfortunately, our knowledge of both past climate change and the responsible forcings are too poor to reliably determine ΔT_{2x} from past data. Wigley and Raper (1987) estimate that if all of the warming of the past 100 years was due to greenhouse gases, then ΔT_{2x} would be approximately 2°C. If however, one allows for other possible forcings, natural variability, uncertainties in ocean heat uptake and the transient response, and for uncertainties in preindustrial greenhouse gas concentrations (see below; Hansen et al., 1985; Wigley and Schlesinger, 1985; Wigley et al., 1986), then the climate record of the last 100 years is consistent with any ΔT_{2X} between 0 and 6°C (Wigley, personal communication).

Due to the various problems with direct empirical approaches, mathematical models of the climate system are the primary tool for estimating climate sensitivity. While they have inherent errors, they can isolate the greenhouse forcing, and many theoretical calculations can be made to test the importance of various assumptions and various proposed feedback mechanisms. The simplest climate model is the zero-dimensional global average model described in the box below. Models that are one-dimensional in the vertical, often called "radiative-convective" models, and that are one-dimensional in the horizontal, often called "energy-balance" models, are very useful for quickly and inexpensively testing various components of the climate system. In order to calculate the location of future climate change, however, and in order to incorporate all the important physical interactions, especially with atmospheric circulation, fully three-dimensional general circulation models (GCMs) are necessary. These sophisticated models solve simultaneous equations for the conservation of energy, momentum, mass, and the equation of state on grids with horizontal resolution ranging from 3 to 8 degrees of latitude by 3 to 10 degrees of longitude and with varying vertical resolution. The radiation schemes attempt to account for the radiatively significant gases, aerosols and clouds. They generally use different schemes for computing cloud height, cover and optical properties. The models also differ in their treatment of ground hydrology, sea ice, surface albedo, and diurnal and seasonal cycles (Schlesinger and Mitchell, 1988). Perhaps the most important differences lie in the treatment of oceans, ranging from prescribed sea surface temperatures, to "swamp" oceans with mixed layer thermal capacity but no heat transport, to mixed layers with specified heat transport, to full oceanic GCMs.

A series of reviews by the National Academy of Sciences (NAS, 1979, 1983, 1987) as well as the "State-of-the-Art" report of the Department of Energy (MacCracken and Luther, 1985) have concluded that the equilibrium sensitivity of climate to a $2xCO_2$ forcing (ΔT_{2X}) is probably in the range of 1.5 to 4.5°C. An independent review by Dickinson (1986) attempts to quantitatively combine the uncertainties indicated by the range of recent GCM results and concludes that the range should be broadened to 1.5-5.5°C. The GCM result of Wilson and Mitchell (1987) giving ΔT_{2X} = 5.2°C was published after all of the reviews cited here. Dickinson's estimates of the contributions of the individual factors to climate sensitivity are shown in Figure 3-6. The largest positive feedback is from changes in the amount and distribution of water vapor. Substantial positive feedback may also be contributed by changes in sea ice and surface albedo and clouds, although the uncertainty range includes the possibility that clouds contribute significant negative feedback. The differences in the strength of these feedbacks between models is the result of different parameterizations of the relevant processes as well as differences in the control ($1xCO_2$) simulation (Cess and Potter, 1988). Even though the exact value of ΔT_{2X} is not known, we can study the potential impact of climatic warming caused by greenhouse gases by choosing scenarios that span the range of theoretical calculations. Thus, we adopt 2-4°C as a putative one standard deviation (1σ) confidence interval about the center of the range proposed by the National Academy of Sciences, and the range proposed by Dickinson (1.5 to 5.5°C) as 2σ bounds for subsequent modeling (Chapter V). When the biogeochemical feedbacks discussed above are also considered, a ΔT_{2X} as great as 8-10°C cannot be ruled out (Lashof, 1989).

THE RATE OF CLIMATIC CHANGE

The Earth's surface does not immediately come to an equilibrium following an increase in radiative forcing. Excess radiation captured by the Earth heats the land surface, the ocean, and the atmosphere. The effective heat capacity of the oceanic part of the climate system, in particular, is enormous. The result is that the warming realized in any given year may be substantially less than the warming that would occur in equilibrium if greenhouse gas concentrations were fixed at their levels in that year. Hundreds of years would be required for the entire ocean to equilibrate with the atmosphere, but only the surface layer (about 100 m) is well mixed by winds and therefore tightly linked to climate in the short term. The heat capacity of the surface layer is about 1/40th that of the entire ocean and this layer by itself would equilibrate with a response time (the time required to reach 1 - 1/e, or 63%, of the equilibrium response) of 2-15 years, depending on the climate sensitivity and assumed mixed layer depth. The equilibration time is longer if the climate sensitivity is greater because the feedback processes that increase climate sensitivity respond to the realized changes in climate, not to the initial change in forcing (Hansen et al., 1985). When the transfer of heat from the mixed layer into the deep ocean is considered, it is impossible to characterize the oceanic response with a single time constant (Harvey and Schneider, 1985; Wigley and Schlesinger, 1985).

While the main features of ocean circulation and mixing, and therefore the rate of heat and carbon uptake, have been identified, they are not well defined or modeled on a global scale. The theory and modeling of ocean circulation are currently limited by the inadequacy of the database (Woods, 1985). The development of Ocean General Circulation Models (OGCMs) lags significantly behind their atmospheric counterparts, mainly because it is difficult and expensive to obtain the necessary data with sufficient temporal and spatial coverage, because fewer scientists have addressed this problem, and because a large amount of computer power is needed to resolve the necessary time and space scales. Due to these problems it may be a decade or more before OGCMs reach the state of development achieved by current atmospheric GCMs.

Lacking well-tested OGCMs, the main tools used so far to investigate ocean heat uptake have been highly parameterized models, very similar to those used for carbon (see Chapter II). These models are calibrated with data on the penetration of tracers such as tritium and ^{14}C produced by atmospheric nuclear weapons tests during the 1950s and early '60s and/or with the steady-state profiles of various ocean parameters, such as natural ^{14}C and temperature. The simplest models that yield a plausible time-dependence for heat (and carbon) uptake lump the entire ocean into two compartments: A well-mixed surface layer and a deep ocean compartment in which mixing is parameterized as a diffusive process (Box-Diffusion or BD model). This approach was introduced by Oeschger et al. (1975) for modeling carbon uptake, and has been applied to ocean heat absorption by Hansen et al. (1985) and Wigley and Schlesinger (1985), among others. A more elaborate version of this model which includes a representation of upwelling implicitly balanced by high-latitude bottom-water formation (Upwelling-Diffusion or UD model), has been used by Hoffert et al. (1980), Harvey and Schneider (1985), and Wigley and Raper (1987). The addition of an upwelling term allows the observed mean thermal structure of the ocean to be approximated (Hoffert et al., 1980), but given the highly parameterized nature of both of these models, there is no convincing reason to favor one approach over the other for modeling small perturbations to heat flows.

The response time, τ, of Box-Diffusion models is proportional to $\kappa(\Delta T_{2x})^2$, where κ is the diffusion constant used to characterize deep ocean mixing (Hansen et al., 1985; Wigley and Schlesinger, 1985). Data on the penetration of tracers into the ocean suggests that κ = 1-2 cm^2/s (Hansen et al., 1985). Hoffert and Flannery (1985) have argued that mixing rates derived from tracers may be too high for heat because mixing rates are highest along constant density surfaces, which are nearly parallel to ocean isotherms. On the other hand, in a preliminary coupled GCM-OGCM run, Bryan and Manabe (1985) found that heat was taken up more rapidly than with a passive tracer because of reduced upward heat convection. Using a range of 0.5-2 cm^2/s for κ and the 1σ range for ΔT_{2x} given above (2-4°C) in the equation derived by Wigley and Schlesinger (with their recommended values for other parameters) yields τ = 6-95 years.[2] Correspondingly, the warming expected by now, based on past increases in greenhouse gases and assuming no other climate forcings, is roughly 40-80% of the equilibrium warming (Wigley and Schlesinger, 1985). In other words, even if greenhouse gas concentrations could be fixed at today's level, the Earth would still be subject to significant climatic change that has yet to materialize. The large uncertainty surrounding ocean heat uptake, combined with uncertainty about potential climate forcings other than those from greenhouse gases, also implies that it is not possible to obtain a useful constraint on ΔT_{2x} from the observed temperature record as discussed above (see also Hansen et al., 1985; Wigley and Schlesinger, 1985).

Experiments with Upwelling-Diffusion models demonstrate the importance of the bottom water formation process for the rate of ocean heat uptake. The impact of using an Upwelling-Diffusion ocean model rather than a Box-Diffusion ocean model is that the heat that diffuses into the thermocline is pushed back toward the mixed layer, which decreases the effective heat capacity of the ocean and the time constant for tropospheric temperature adjustment, *assuming that the upwelling rate and the temperature at which bottom water is formed do not change*. If the initial temperature of the downwelling water is assumed to warm as much as the mixed layer, however, then a UD model actually takes up more heat in the ocean than a BD model, leading to a larger disequilibrium between a given radiative forcing scenario and the expected realized warming. While there are reasons to think that the temperature of Antarctic Bottom Water will not increase as climate changes, the temperature of North Atlantic Deep Water could increase or decrease (Harvey and Schneider, 1985). Furthermore, there is no reason to assume that the rate of bottom-water formation will remain constant as climate changes. The tropospheric temperature could even overshoot equilibrium if the average bottom-water temperature cools as the surface temperature warms or if the upwelling rate increases with warming (Harvey and Schneider, 1985). One must also recognize the potential for sudden reorganizations of the ocean-atmosphere circulation system as suggested by Broecker (1987), which could lead to discontinuous, and perhaps unpredictable, changes in climate that cannot be included in the models used in this report.

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[2] It is important to note that the actual response does not correspond to exponential decay with a single time constant, so that while τ gives the time required for one e-folding and is a useful measure, it would not apply to subsequent e-foldings (the time constant would be substantially longer) and must be interpreted with care.

Another major limitation of the BD and UD models generally used to analyze the climate transient problem is that they have limited or no spatial resolution (at best hemispheric, land-sea) and thus cannot consider spatial heterogeneity in either the magnitude or rate of climatic change. Work at the Goddard Institute for Space Studies (Hansen et al., 1988) has produced one of the few three-dimensional time-dependent analyses of climatic change that have been published to date. This study employed three simple, but reasonably realistic, scenarios of future greenhouse gas concentrations and volcanic eruptions. The results suggest that the areas where warming is initially most prominent relative to interannual variability are not necessarily those where the equilibrium warming is greatest. For example, low-latitude ocean regions warm quickly because ocean heat uptake is limited by strong stratification in these regions. Warming is also prominent in high-latitude ocean areas where a large equilibrium warming is expected due to increased thermal inertia as sea ice melts. Global average temperatures are used in this report as an indicator of the rate and magnitude of global change but, as these results emphasize, it must be recognized that major variations among regions are a certainty.

CONCLUSION

The changing composition of the atmosphere will in turn drive significant changes in the Earth's climate. These changes may have already begun, but because of the uncertainties in temperature data sets and the complexity of the interaction between climate sensitivity and the transient response, definitive predictions are subject to a good deal of controversy at this time. *Whether next year is warmer or cooler than this year, however, has no direct bearing on how the greenhouse effect should be viewed.* Internal fluctuations or countervailing forcings may temporarily mask the warming due to increasing concentrations of greenhouse gases or make the climate warmer than expected solely from greenhouse warming. Therefore, to derive our estimates of the magnitude and rate of change that can be expected during the next century we must continue to rely on model calculations, which indicate that by early in the next century the Earth could be warmer than at any time during the last million years or more, and that the rate of change could be unprecedented in Earth history.

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CHAPTER IV

HUMAN ACTIVITIES AFFECTING TRACE GASES AND CLIMATE

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FINDINGS

Various human activities affect the Earth's climate by altering the level of trace gases in the atmosphere. These activities include energy consumption, particularly fossil-fuel consumption; industrial processes; land use change, particularly deforestation; and agricultural practices such as waste burning, fertilizer usage, rice production, and animal husbandry. Economic development and population growth are key factors affecting the level of each activity.

- Population levels and growth rates have increased tremendously over the last 200 years. Between 1650 and 1980, the global population doubling time shrunk from 200 to 35 years. At the beginning of this century, global population was about 1.6 billion; in 1987, it reached 5 billion. By the early part of the next century total population is likely to reach 8 billion. The rate of population increase is most acute in the developing regions, particularly Afric and Asia where annual rates of growth exceed 2%.

- Fossil fuel combustion emits carbon dioxide and other radiatively important gases and is the primary cause of atmospheric warming. Energy consumption currently accounts for more than five of the six to eight billion tons of carbon dioxide emitted to the atmosphere annually from anthropogenic sources. Between 1950 and 1986, annual global fossil fuel consumption grew 3.6-fold and annual carbon dioxide emissions grew 3.4-fold.

- Emissions of other trace gases due to fossil fuel consumption are more uncertain. Approximately 0 to 2 million tons nitrogen as nitrous oxide, 20 million tons nitrogen as nitrogen oxides, and 180 million tons carbon as carbon monoxide are emitted annually from fossil fuel combustion. Leaking and venting of natural gas contributes approximately 20 to

50 million tons methane annually to the atmosphere, and coal mining contributes approximately 25 to 45 million tons methane.

- Three significant non-energy sources of greenhouse gases are associated with industrial activity: Production and use of chlorofluorocarbons (CFCs), halons, and chlorocarbons; waste disposal in landfills; and cement manufacture. Production of CFC-11 and CFC-12 grew 4.7-fold between 1960 and 1985. Consumption of major CFCs and halons reached nearly one million tons in 1985. An international agreement (the Montreal Protocol), however, came into force on January 1, 1989 to reduce future production of certain CFCs and halons. Anaerobic decay of organic wastes in landfills currently contributes approximately 30-70 million tons of methane to the atmosphere annually. Cement production, which has increased sevenfold since the 1950s, contributed approximately 134 million tons carbon as CO_2 to the atmosphere in 1985.

- Land use change has resulted in substantial emissions of greenhouse gases to the atmosphere. Since 1850, approximately 15% of the world's forests have been converted to agricultural and other land uses. Currently, deforestation contributes between one-tenth and one-third of the total anthropogenic carbon dioxide emissions to the atmosphere, i.e., between 0.4 to 2.6 billion tons of carbon. Between one-quarter and one-half of the world's swamps and marshes also have been destroyed by man. Wetlands currently contribute approximately one-fifth of the total methane emissions to the atmosphere; continued changes to wetlands could significantly alter the global methane budget. Biomass burning, in addition to contributing to the atmospheric concentrations of carbon dioxide, contributes approximately 10 to 20% of total annual methane emissions, 5 to 15% of the nitrous oxide emissions, 10 to 35% of the nitrogen oxide emissions, and 20 to 40% of the carbon monoxide emissions.

- Three agricultural activities directly result in major contributions to atmospheric emissions of greenhouse gases: animal husbandry, rice cultivation, and nitrogenous fertilizer use. Domestic animals, which produce methane as a by-product of enteric fermentation, currently contribute approximately 65 to 85 million tons of methane annually. Over the past several decades, domestic animal populations have grown by up to 2% annually. Methane is also produced by anaerobic decomposition in rice paddies. Currently, about one-fifth of annual methane emissions, or between 60 and 170 million tons, comes from rice cultivation. Rice production has grown rapidly since the mid-1900s due to increases in crop acreage, double cropping, and higher yields. Between 1950 and 1984 rice production increased nearly threefold, and harvested area grew by about 70%. Use of nitrogenous fertilizers results in nitrous oxide emissions, either directly from the soil, or indirectly from groundwater. Global use of organic and inorganic fertilizers has risen markedly, and nitrogen-based fertilizers increased their market share of total inorganic fertilizer consumption from 28% in 1950 to 64% in 1981. Nitrogenous fertilizer use may contribute between 0.14 and 2.4 million tons nitrogen as nitrous oxide per year to the atmosphere.

- In addition to the human activities that directly affect trace gas emissions, future concentrations of greenhouse gases will be influenced by feedback processes resulting from humans living in a world that has undergone climatic change. Two potential feedbacks of increased temperatures, which may counteract each other to some extent, are increased energy demand for air conditioning in the summer, and decreased energy demand for heating in the winter.

INTRODUCTION

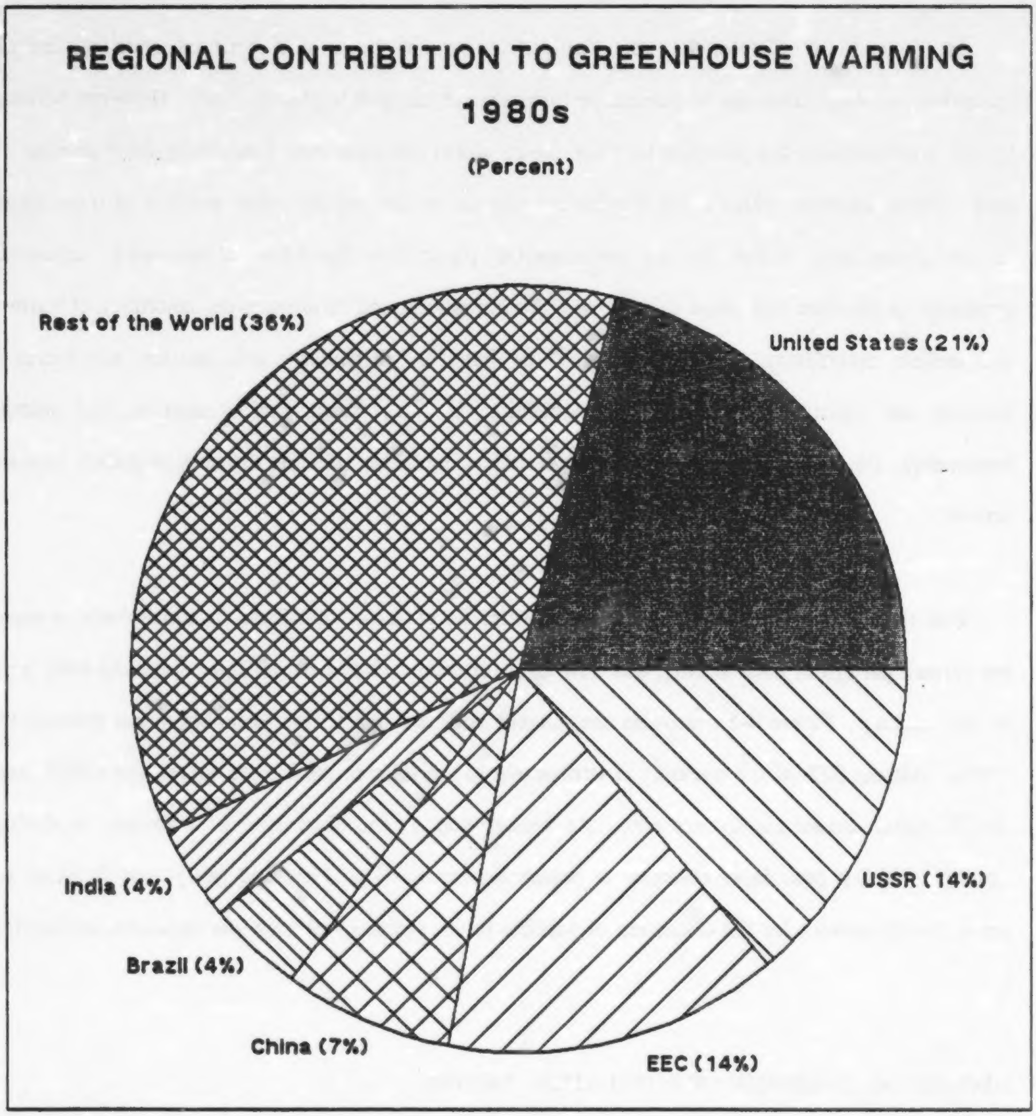
As discussed in Chapter III, the Earth's climate has been in a constant state of change throughout geologic time due to natural perturbations in the global geobiosphere. However, various human activities have the potential to cause future global warming over a relatively short amount of time. These activities, which affect the Earth's climate by altering the concentrations of trace gases in the atmosphere, include energy consumption, particularly fossil-fuel consumption; industrial processes (production and use of chlorofluorocarbons, halons, and chlorocarbons, landfilling of wastes, and cement manufacture); changes in land use patterns, particularly deforestation and biomass burning; and agricultural practices (waste burning, fertilizer usage, rice production, and animal husbandry). Population growth is an important underlying factor affecting the level of growth in each activity.

This chapter describes how the human activities listed above contribute to atmospheric change, the current pattern of each activity, and how levels of each activity have changed since the early part of this century. Figure 4-1 illustrates the current contributions to the greenhouse gas buildup by region. Almost 50% of the warming is attributable to activities in the United States, the USSR, and the European Economic Community. As background to the discussion of trace-gas producing activities, we first provide an overview of population trends. This historical perspective is meant to serve as a framework for the discussion of possible future scenarios of trace-gas emissions in Chapter V.

HISTORICAL OVERVIEW OF POPULATION TRENDS

One of the major factors affecting trends in greenhouse gas emissions is the increase in human population. As population levels rise, increasing pressures are placed on the environment as the larger population strives to feed and clothe itself and achieve a higher standard of living. Without

FIGURE 4-1



REGIONAL CONTRIBUTION TO GREENHOUSE WARMING 1980s (Percent)

Figure 4-1. Estimated regional contribution to greenhouse warming for the 1980s, based upon regional shares of current levels of human activities that contribute to greenhouse gas emissions. (Sources: U.S. EPA, 1988a; United Nations, 1987; U.S. BOM, 1985; IRRI, 1986; FAO, 1986a, 1987; Bolle et al., 1986; Rotty, 1987; Lerner et al., 1988; Seiler, 1984; WMO, 1985; Hansen et al., 1988; Houghton et al., 1987; Matthews and Fung, 1987.)

changes in the methods used to meet people's needs, higher population levels invariably lead to increased emissions of greenhouse gases.

Global Population Trends

Not only has global population grown rapidly over the past few centuries, but the rate of growth has also increased (see Figure 4-2). World population in the year 1 A.D., approximately 0.25 billion, doubled by 1650 (Wagner, 1971). By 1850 (i.e., 200 years later), global population had roughly doubled again to 1.1 billion. The global population doubling time has continued to decline -- 80 years later, in 1930, world population was 2 billion. By 1975 global population had reached 4 billion, and according to some estimates the population will double once again within 35 years (world population reached 5 billion in 1987). Moreover, despite recent declines in the world's annual population growth rate (IIED and WRI, 1987), world population is expected to continue to grow rapidly. Several studies estimate that world population will exceed 8 billion by 2025 (Zachariah and Vu, 1988; U.S. Bureau of the Census, 1987). Such rapid population growth can be expected to result in increasing pressure on the global environment, particularly as the burgeoning human population strives to improve its living standards through economic growth.

Population Trends by Region

The rapid population growth in recent decades has not occurred uniformly around the world (see Figure 4-2). Between 1950 and 1985, population in developed countries increased by 41%, compared to 117% in developing countries (IIED and WRI, 1987). Recent trends indicate these differences will continue: Annual growth rates in the developed countries are generally less than 1%, while many developing countries continue to experience rates of growth between 2 and 3% (see Table 4-1). These higher growth rates in the 20th century in developing countries have been due primarily to the combined effects of declining death rates and continued high birth rates.

FIGURE 4-2

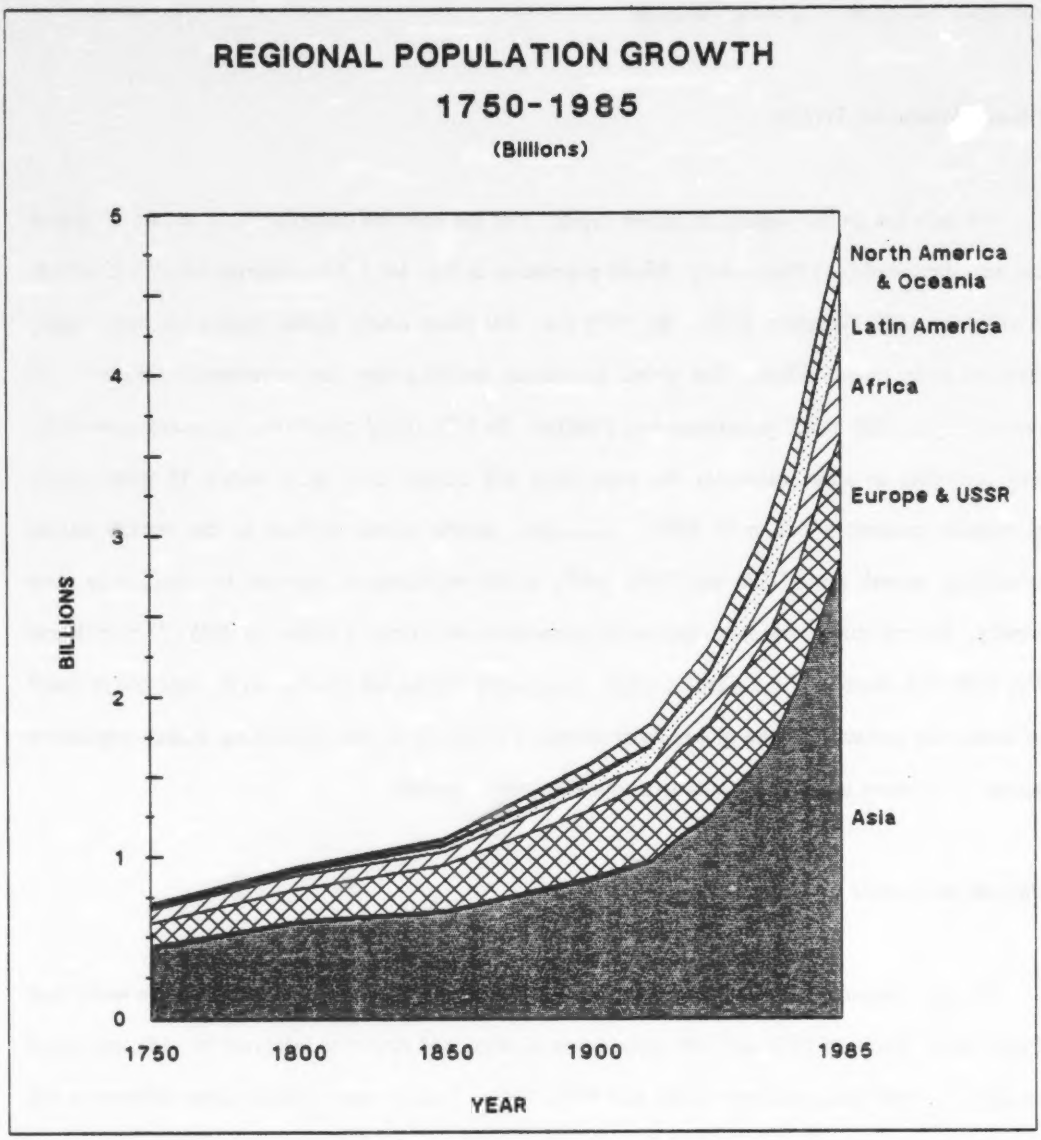


Figure 4-2. Since about 1850, global population has grown at increasingly rapid rates. In 1850, the population doubling time was approximately 200 years; by 1975, the doubling time had declined to approximately 45 years. Most of the growth has occurred in the developing world, particularly Asia. (Sources: Matras, 1973; Hoffman, 1987.)

TABLE 4-1

Regional Demographic Indicators

Region	Total Fertility[a] 1980-85	Infant Mortality[b] 1980-85	Annual Population Growth Rate 1980-85 (percent)
North America	1.83	11	0.90
Europe	1.88	15	0.30
East Asia	2.34	36	1.22
Oceania	2.65	31	1.51
Caribbean	3.34	65	1.53
Southeastern Asia	4.11	73	2.05
Latin America	4.17	61	2.34
Southern Asia	4.72	115	2.14
Western Asia	5.22	81	2.79
Africa	6.34	112	2.92
World Average	3.52	60	1.67

[a] The total fertility rate is the average number of children that a woman bears in a lifetime.

[b] The infant mortality rate is the average number of infant deaths (deaths before the first birthday) per 1,000 live births.

Source: Adapted from IIED and WRI, 1987.

Industrialized Countries

Population growth rates in the industrialized countries are substantially lower compared with growth rates in the developing world. For example, while most developing countries contend with growth rates that will double their populations within 20-40 years, current growth rates in North America and Europe will lead to a doubling within about 100 years and 250 years, respectively (IIED and WRI, 1987). This trend toward lower growth rates is due to many complex economic and social factors, including the changing role of women in the labor force, the higher economic costs of child rearing, and the reduced need for children as a labor pool.

Developing Countries

The highest rates of population growth are in the developing countries: From 1950 to 1985 developing countries increased their share of the world's population from 66.8% to 75.6% (IIED and WRI, 1987). During this time Asia's population grew from 1.3 to 2.7 billion, Africa's from 224 to 555 million, and Latin America from 165 to 405 million. Key trends are summarized below.

Africa. Africa currently has the highest fertility rates and population growth rates in the world. Its growth rate has increased recently: Between 1955 and 1985, Africa's average annual growth rate increased from 2.3% to 2.9%. The total fertility rate (i.e., average number of children that a woman bears in a lifetime) is six or higher in 38 African countries, most of which have experienced declining infant mortality rates (infant deaths per thousand live births) over the past 20 years (IIED and WRI, 1987). For example, in Kenya, where the total fertility rate is 7.8, the infant mortality rate fell from 112 to 91 between 1965 and 1985. Between 1965 and 1985, the crude birth rate (births per thousand population) for Kenya grew by 4.7%, while the crude death rate fell by 37.7%. The average annual growth rate reached 4.1% in the 1980s (World Bank, 1987). The United Nations expects the African population to continue to grow rapidly, with the average annual growth rate increasing to 3% in 1990 (United Nations, 1986).

Asia. From 1850 to 1950, Asia experienced the largest increase in population in the world (Ehrlich and Ehrlich, 1972). Rates of growth have continued at high levels -- annual growth rates since 1960 have exceeded 2%. These rates are likely to remain high in several Asian countries in future years (United Nations, 1986). For example, China currently is the most populous country in the world, with 22% of the world's total (Ignatius, 1988). Although its strong population policy of one child per family helped to halve the 2% annual growth rates of the 1960s, growth rates have recently turned upward, approaching 1.5% annually. This trend of growth could lead to population levels in China in excess of 1.7 billion by 2025.

India's population has also been rapidly expanding. It is the second most populous country in the world (United Nations, 1986), with 765 million people as of 1985. India's rate of growth has been relatively high this century, although it has declined in recent years; in 1960 its annual rate of growth was 2.3%, but has since dropped to 1.7% (IIED and WRI, 1987). Despite this recent decline, its population is expected to grow for many years; e.g., the United Nations estimates that India's population will be over 1.2 billion by 2025 (United Nations, 1986).

Latin America. Latin America currently has one of the highest population growth rates in the world: From 1980 to 1985 the annual rate of growth averaged 2.3% for the region (IIED and WRI, 1987), although these rates of growth varied substantially between countries. Argentina, Chile, and Uruguay have the lowest growth within Latin America, while countries such as Bolivia, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Paraguay, and Venezuela have annual population growth rates that exceed 2.5%. Fertility rates have been declining throughout the region due to industrialization, urbanization, rising incomes, and official population policies, although one source estimates that Latin America's share of world population will nonetheless increase from 8.4 to 9.5% between 1985 and 2025 (IIED and WRI, 1987). The two population projection sources used in this report (U.S. Bureau of the Census, 1987, and Zachariah and Vu, 1988; see Chapter V) project that by 2025, Latin America's share of world population will grow to 9.1 and 8.7%, respectively.

ENERGY CONSUMPTION

The major human activity affecting trace-gas emissions is the consumption of energy, particularly energy from carbon-based fossil fuels. As discussed in Chapter II, global carbon dioxide (CO_2) emissions from anthropogenic sources currently range from 6 to 8 petagrams (Pg) of carbon (C) annually, with commercial energy consumption accounting for approximately 65-85% of this total.[1] Non-commercial (biomass) energy consumption accounts for approximately 7%. Energy consumption and production also produce substantial amounts of other greenhouse gases, including carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x, or NO and NO_2), and nitrous oxide (N_2O).[2]

This section explores the role of energy consumption in climate change. We first discuss the world's increasing reliance on fossil fuels, the roles that fossil-fuel production (e.g., coal mining and oil drilling) and fossil-fuel combustion play in the emission of trace gases to the atmosphere, and the implications of the continuation of current energy consumption patterns on future global warming.

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[1] Anthropogenic sources of trace gases are those resulting from human activities, e.g., combustion of fossil fuels. These sources are distinguished from natural sources, since emissions from anthropogenic sources result in unbalanced trace-gas budgets and accumulation of gases in the atmosphere.

[2] Throughout the report these gases are often referred to as greenhouse gases, although strictly speaking, CO and NO_x are not greenhouse gases since they do not directly affect radiative forcing (see Chapter II). These two gases indirectly affect global warming due to their chemical interactions with other gases in the troposphere. As a result, for simplicity, we shall refer to them as greenhouse gases.

History of Fossil-Fuel Use

Prior to the discovery and development of fossil fuels (coal, oil, and natural gas), people relied on readily-available energy resources such as wood and other forms of biomass (i.e., living matter), as well as water and wind, to satisfy their basic energy needs. Since the beginning of the 19th century, fossil fuels have played an increasingly important role in the world economy, particularly for developed countries, by providing the energy required for industrial development, residential and commercial heating, cooling, and lighting, and transportation services. Fossil fuels now provide about 85% of the world's total energy requirements. This dependence on fossil fuels is greatest in industrialized countries, where over 95% of all energy needs are provided by fossil fuels, compared with about 55% in developing countries (Hall et al., 1982).[3]

Global consumption of fossil fuels has increased rapidly over the past century as human populations and their economic activities have grown, resulting in the development of additional fossil-fuel resources. Since 1950, global primary energy consumption has increased nearly fourfold (Figure 4-3), with energy consumption per capita approximately doubling. In 1985, 42% of global energy demand was supplied by liquid fossil fuels (primarily petroleum); solid fuels (coal) supplied 31%, natural gas, 22%, and other fuels combined accounted for 5% of the market share.[4] These relative proportions have changed considerably since 1950, when coal supplied 59% of total commercial energy requirements, liquids, 30%, natural gas, 9%, and other fuels, 2%.

The increase in fossil fuel consumption over the last century has caused a substantial increase in the amount of CO_2 emitted to the atmosphere. Carbon dioxide emissions from fossil fuels grew

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[3] In some developing countries, the dependence on biomass can approach 95 percent of total energy requirements.

[4] Non-commercial biomass estimates are not included in these figures.

FIGURE 4-3

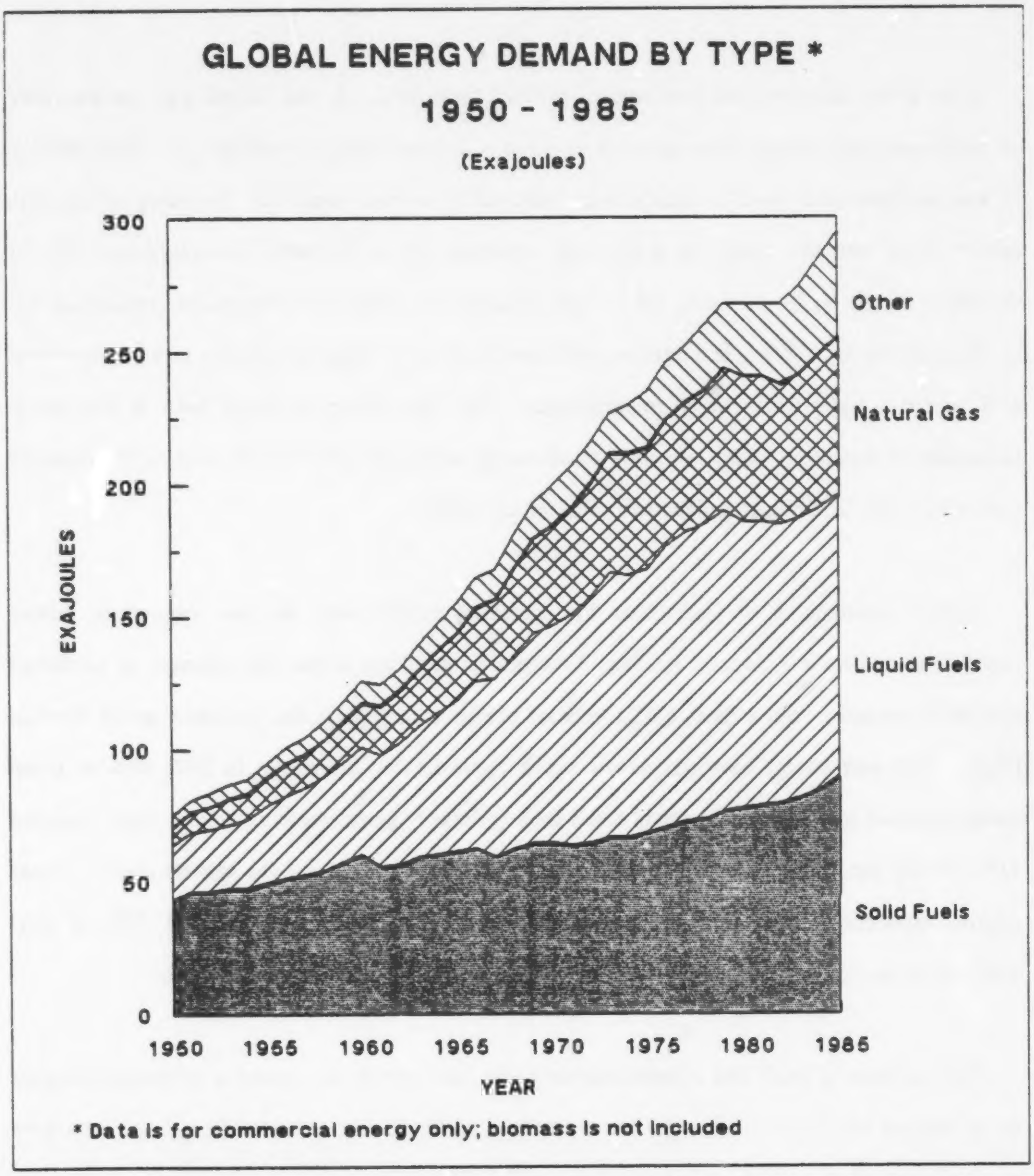

Figure 4-3. Global demand for fossil fuels has more than tripled since 1950. Today, about 85% of the world's energy needs are met by fossil fuels. (Sources: United Nations, 1976, 1982, 1983, 1987.)

from less than 0.1 Pg C annually in the mid-nineteenth century, to about 5.4 Pg C in 1986 (see Figure 4-4).[5] This rate of increase is about 3.6% per year and is the major reason why atmospheric CO_2 concentrations increased from about 290 ppm in 1860 to about 348 ppm as of 1987 (Farman et al., 1985). Currently fossil fuel combustion also contributes approximately 0-2 Tg N as N_2O, 20 Tg N as NO_x and 180 Tg C as CO annually to the atmosphere.

In recent decades there has also been a significant shift in global energy use patterns. In 1950, countries belonging to the Organization for Economic Cooperation and Development (OECD) consumed about three fourths of all commercial energy supplies, the centrally-planned economies of Europe and Asia, 19%, and developing countries, 6% (United Nations, 1976, 1983).[6] By 1985 OECD countries consumed just over one-half of all commercial energy globally, while the European and Asian centrally-planned economies and the developing countries had increased their relative shares to 32% and 15%, respectively (see Figure 4-5). Between 1950 and 1985, commercial energy use per capita in the OECD grew from 93 to 189 gigajoules per capita (GJ/cap) (103%), in centrally-planned economies from 16 to 59 GJ/cap (269%), and in the developing countries from 3 to 18 GJ/cap (500%).[7] The proportion of energy consumed by the OECD is expected to decline further as the developing world continues to experience population growth and economic development and, thus, significantly expands their energy requirements (Chapter V).

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[5] In 1986 CO_2 emissions from fossil fuels were approximately 5370 million metric tons C, or 5.37 Pg C. 1 billion metric tons = 1 gigaton = 1 Pg = 10^{15} grams.

[6] The OECD countries include the U.S., Canada, Japan, Australia, New Zealand, the United Kingdom, France, Spain, Portugal, the German Federal Republic, Belgium, the Netherlands, Sweden, Norway, Finland, Italy, Ireland, Iceland, Denmark, Austria and Switzerland.

[7] 1 GJ = 1 gigajoule = 10^9 joules. 1055 joules = 1 Btu.

FIGURE 4-4

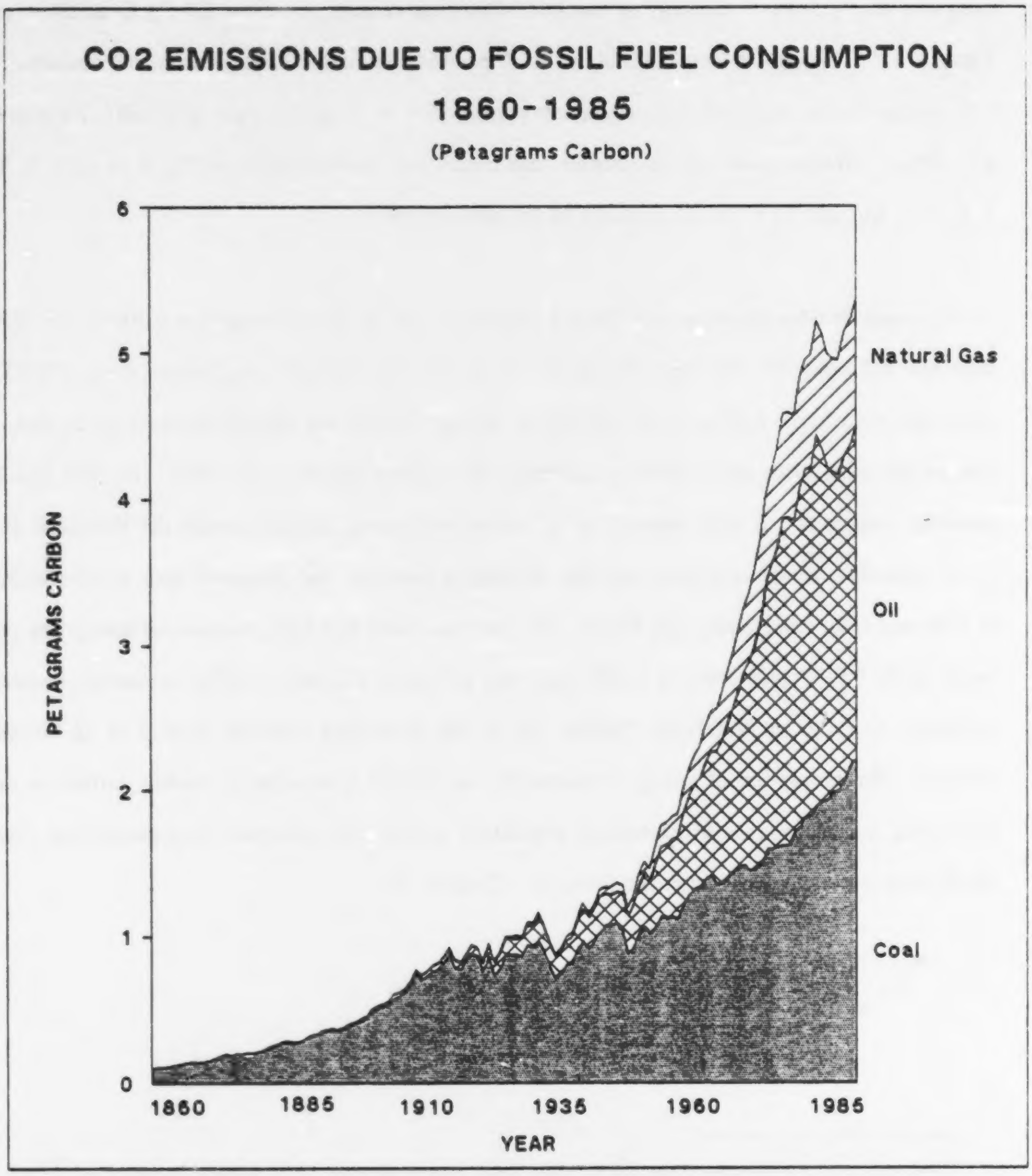

Figure 4-4. Carbon dioxide emissions from fossil fuel combustion have grown from less than 0.1 Pg C in the mid-1850s to approximately 5.4 Pg C in 1986. This is the major reason why the atmospheric concentration of CO_2 increased from approximately 290 ppm in 1860 to approximately 348 ppm in 1987. (Sources: Rotty and Masters, 1985; Rotty, 1987, pers. communication.)

FIGURE 4-5

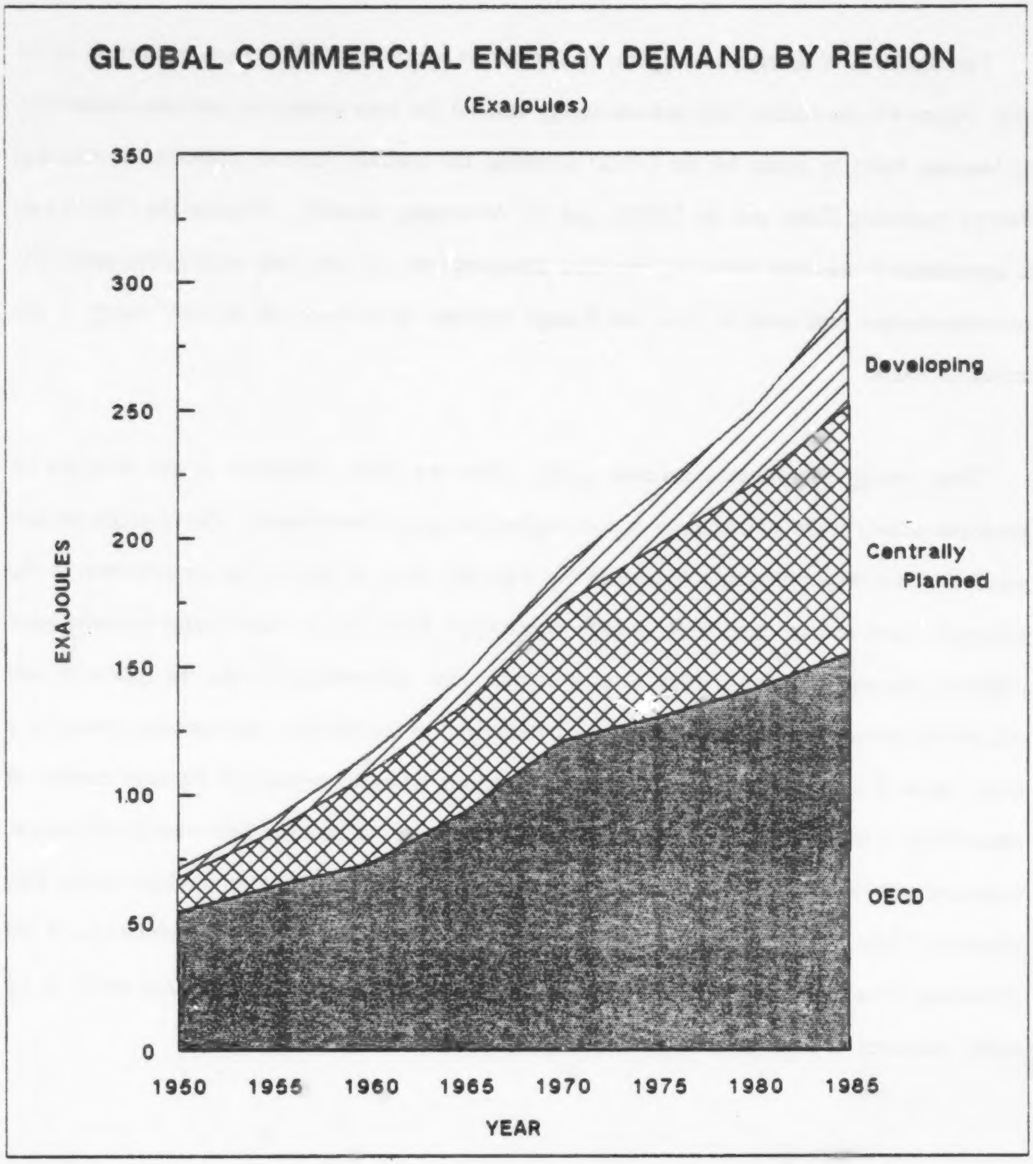

Figure 4-5. Primary energy use by region. Between 1950 and 1985, the share of global energy demand for the OECD declined, while that for the centrally planned and developing economies increased. (Sources: United Nations, 1982, 1987.)

Current Energy Use Patterns and Greenhouse Gas Emissions

The allocation of energy consumption among sectors varies considerably from one region to the next. Figure 4-6 summarizes 1985 end-use energy demand (for both commercial and non-commercial, or biomass, fuels) by sector for the OECD countries, the centrally-planned economies of Asia and Europe (including China and the USSR), and the developing countries. Whereas the OECD split is approximately one-third industrial, one-third transportation, and one-third residential/commercial, centrally-planned economies of Asia and Europe consume more than 50% of their energy in the industrial sector.

These energy consumption patterns partly reflect the basic differences in the structure of economic activity at the current stage of each region's economic development. The centrally-planned economies and the developing countries devote a greater share of their energy requirements to the industrial sector because they are at a stage of economic development where energy-intensive basic industries account for a large share of total output, while infrastructure in the transportation and commercial sectors has not been extensively developed. In the OECD, transportation consumes a larger share of total energy compared with other regions, primarily because of the large number of automobiles in the OECD. For example, in the U.S. there are 550 cars and light trucks/1000 people, compared with 60 cars and light trucks/1000 people in the USSR, and 6 cars and light trucks/1000 people in China. Also, biomass is very important to the residential energy requirements of the developing economies compared with those of industrialized countries; the industrial sector is the major consumer of fossil fuels in most developing countries.

FIGURE 4-6

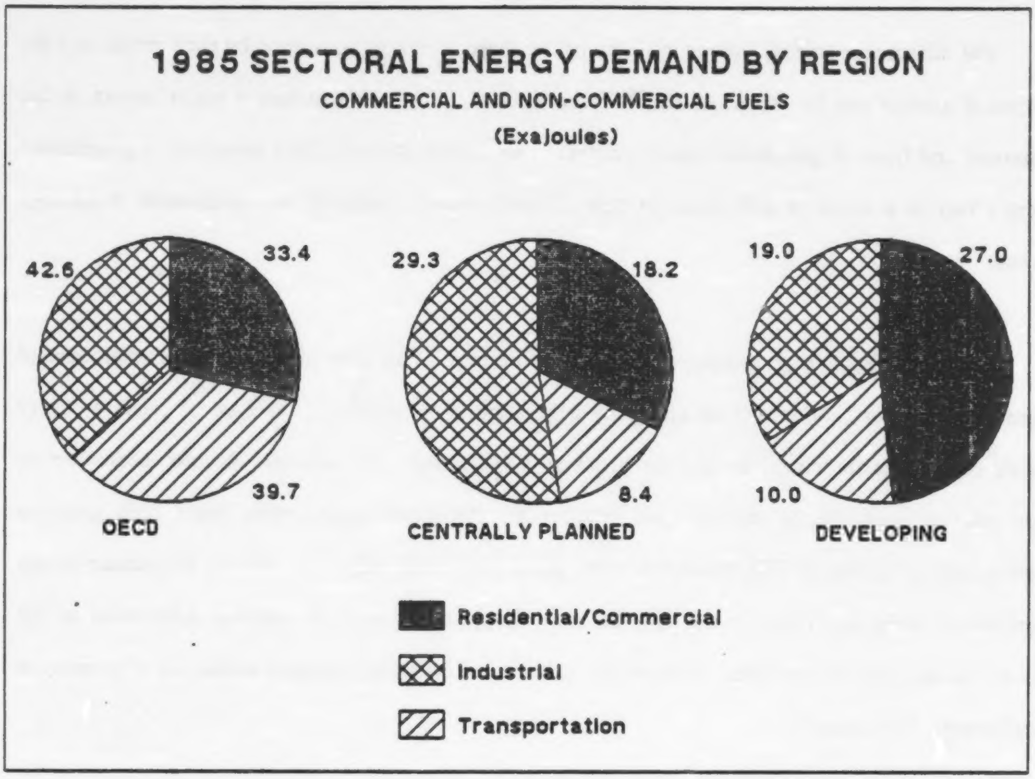

Figure 4-6. End-use energy demand by sector for three global regions. While energy demand in the OECD countries is split almost equally between the three sectors, over 50% of the energy in the centrally planned countries is consumed by the industrial sector, and almost 50% of the energy in the developing countries is consumed by the residential/commercial sector. (Sources: Sathaye et al., 1988; Mintzer, 1988.)

Emissions by Sector

The differences among regions in terms of the share of energy consumed by each sector and the types of applications for which the energy within each sector is used can have a major impact on the amount and types of greenhouse gases emitted. This section discusses how emissions of greenhouse gases vary as a result of differences in type of fossil energy consumed and combustion technology used.

Electric Utility Sector. Energy is increasingly desired in the form of electricity. The amount of greenhouse gases produced from electricity generation is a function of the type of primary energy used to produce the electricity and the production technology. For example, nuclear, hydroelectric, or solar primary energy sources emit little or no greenhouse gases, while fossil fuels generate substantial quantities of CO_2, as well as other gases (see Table 4-2). The amount of greenhouse gas emissions varies according to the type of fossil fuel used because of inherent differences in the chemical structure of the fuels. Additionally, the level of emissions varies as a function of production efficiency. For example -

- Coal-fired power plants produce about two to three times as much CO_2 as natural gas-fired units per unit of electricity generated (330 kg CO_2/GJ for a pulverized coal wall-fired unit compared with 120 kg CO_2/GJ for a combined cycle gas-fired unit). Oil-fired units produce more CO_2 than natural gas units produce, but less CO_2 than coal-fired units produce. Within fuel types the emission levels may vary. For example, when natural gas is used as the fuel, combined cycle or ISTIG units produce about 40% lower CO_2 emissions than simple cycle units (see Chapter VII) because of the greater generating efficiency obtained through the use of these technologies.

TABLE 4-2

Emission Rate Differences by Sector
(grams per gigajoule)[a]

Source	Efficiency (%)	CO_2	CO	CH_4	N_2O	NO_x	Total Carbon
Electric Utility (g/GJ delivered electricity)							
Gas Turbine Comb. Cycle	42.0	120,300	70	13	20	400	32,850
Gas Turbine Simp. Cycle	26.4	191,400	110	20	30	640	52,060
Residual Oil Boilers	32.4	230,000	43	2.2	44	590	62,750
Coal - F. Bed Comb. Cycle	35.0	290,000	NA	1.8	40	690	79,090
Coal - PC Wall Fired	31.3	330,000	42	2.0	45	1,400	90,020
Coal - PC Cyclone	31.3	330,000	42	2.0	45	2,600	90,020
Coal - Integrated Gas	27.3	253,600	222	NA	51	760	69,260
Industrial (g/GJ delivered steam for boilers; energy output for others)							
Boilers							
Coal-Fired	80	130,000	110	2.9	18	390	35,510
Residual Oil-Fired	85	88,000	17	3.3	16	180	24,010
Natural Gas-Fired	85	57,000	18	1.5	3.5	71	15,550
Kilns - Coal	65-75	300-350,000	75	1	2	500	81-95,490
Dryer - Natural Gas	30-65	75-170,000	10	1	NA	52	20-46,370
Dryer - Oil	30-65	100-240,000	15	1	NA	160	27-65,460
Dryer - Coal	30-65	155-340,000	170	1	NA	215	42-92,800
Residential/Commercial (g/GJ energy output)							
Wood Stoves	50	[150,000]	17,600	70	NA	190	48,500
Coal Stoves	50	198,000	3,400	NA	NA	170	55,460
Distillate Oil Furnaces	75	111,000	17	7	NA	65	30,290
Gas Heaters	70	101,000	13	1	NA	61	27,550
Wood Boilers	67.5	[138,000]	280	21	6	47	37,770
Gas Boilers	80.9	61,800	10.6	1.4	2.7	53	16,860
Residual Oil Boilers	84.9	86,000	19	1.8	14	183	23,460
Coal Boilers	75.9	135,000	244	13	16	295	36,930
Transportation (g/GJ energy input)							
Rail	NA	69,900	570	13	NA	1,640	19,320
Jet Aircraft	NA	72,800	120	2	NA	290	19,910
Ships	NA	70,000	320	20	NA	830	19,240
Light Duty Gasoline Vehicle	NA	54,900	10,400	36	0.5	400	19,460
Light Duty Diesel Vehicle	NA	73,750	340	2	20	300	20,260
Light Duty Compressed N. Gas Vehicle	NA	50,200	4	120	7	140	13,780

[a] All emission rates, except for the total carbon estimates in the last column, are based on total molecular weight. Total carbon estimates refer only to the total amount of carbon emitted.

NA = Not Available
[ ] = No Net CO_2 if based on sustainable yield

Source: Radian, 1988; except N_2O data, which is based on unpublished EPA data. N_2O emission coefficients are highly uncertain and currently undergoing further testing and review.

Similarly, coal-fired fluidized bed units produce less NO_x emissions than do coal-fired cyclone units because the higher operating temperatures typical of cyclone-units are more conducive to NO_x formation.

Industrial Sector. The industrial sector includes mining, construction, and manufacturing, which are some of the most energy-intensive economic activities. Energy consumption in this sector can be subdivided into four categories:

- Boilers -- Boilers produce steam for many different purposes, including machine drive, on-site electricity production, high-pressure cleaning, and process requirements. Virtually any fuel can be consumed to produce steam (e.g., fossil fuels, biomass, hazardous wastes, by-product wastes, etc.). In the U.S., boilers consume about 30% of all industrial energy.

- Process Heat -- Many industrial processes that do not use steam require the use of some form of heat during production. Examples of process heat applications include ovens, furnaces, dryers, melters, and kilns. The degree of flexibility in fuel choice a consumer may have depends on the process heat application -- some applications may use technologies or production processes that require a particular fuel.[8] Process heat applications consume about 40% of the energy in the U.S. industrial sector.

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[8] For example, some food production processes use natural gas because its relatively clean-burning characteristic allows it to be used when product contamination may be an issue. Similarly, melters in the glass industry are often designed to burn natural gas because of the flame characteristics of this fuel. Use of other fuels would tend to produce an inferior product and likely require the redesign of equipment.

- Feedstocks -- Fuels may be used as a raw material for the production process. Examples of such applications include the conversion of metallurgical coal to coke for use in the manufacture of steel, natural gas for fertilizer production, and petroleum for asphalt. It is usually very difficult to switch to alternative fuels with these applications. In the U.S., feedstocks consume about 15% of industrial energy.

- Other -- This category consists primarily of industrial activities requiring electricity, e.g., lighting, motor drive, etc. These applications account for 15% of all energy consumed by U.S. industry.

The amount of greenhouse gas emissions generated from industrial energy consumption is a function of fuel type and the process in which it is consumed (see Table 4-2 for emissions from selected industrial applications).

Residential and Commercial Sectors. In the residential and commercial sectors the main end-use applications for energy are heating, cooling, cooking, and lighting. The form and amount of energy used to meet these needs varies, as summarized in Table 4-3 for the U.S. and South/Southeast Asia. In developing countries, most of the energy in these two sectors is consumed for cooking purposes, with consumers relying on biomass or kerosene for fuel. In industrialized countries, however, space heating and water heating consume the most energy, which is supplied primarily by fossil fuels and, to some extent, electricity; gas and electricity are the primary energy forms for cooking in industrialized countries. Because of the wide variety of end-use applications, types of energy consumed, and conversion efficiencies in the residential and commercial sectors it is difficult to generalize about emission trends in these sectors; for illustrative purposes, emission coefficients for several major applications in industrialized countries are listed in Table 4-2.

TABLE 4-3

End-Use Energy Consumption Patterns for the Residential/Commercial Sectors

(% of Total Energy)

	Type of Energy			
End-Use	Biomass	Fossil Fuels	Electricity	Total
South/Southeast Asia				
Heating	0	16	NA	NA
Cooling	0	0	NA	NA
Cooking	75	3	NA	NA
Lighting	0	1	NA	NA
TOTAL	75%	20%	5%	100%
United States				
Heating	<1	59	8	67
Cooling	0	0	6	6
Cooking	0	7	3	10
Lighting	0	0	7	7
Other	0	0	10	10
TOTAL	<1%	66%	34%	100%

Sources: Sathaye et al., 1988; Mintzer, 1988; U.S. DOE, 1987; Leon Schipper, pers. communication.

Transportation Sector. As consumers become wealthier, the absolute quantity and share of energy used in the transportation sector increases. For example, as discussed earlier, in many developing countries, such as China, the transportation sector consumes a much smaller portion of the country's energy requirements than the portion consumed by this sector in industrialized countries, such as the United States. Energy requirements in the transportation sector are typically met with fossil fuels, particularly petroleum-based products such as gasoline, diesel, or jet fuel. For example, in 1985 countries belonging to the OECD met 91% of their transportation energy requirements with oil-derived products, 8% with electricity, and the remaining 1% with natural gas and coal (OECD 1987). As countries become wealthier, increased use of petroleum to meet transportation needs can significantly increase greenhouse gas emissions to the atmosphere (see Table 4-2).

The amount and type of greenhouse gases emitted can also be affected by the transportation technology. For example, gasoline vehicles produce about 25% less CO_2 on an energy input basis than do diesel vehicles, while producing substantially more CO. However, the CO is eventually oxidized to CO_2, so the CO_2 emissions attributable to gasoline vehicles are comparable to those of diesel vehicles. Also, the efficiencies of diesel engines are generally greater than those of gasoline engines for a similar vehicle, implying that diesel vehicles would actually have lower effective CO_2 emissions per mile travelled. Similarly, vehicles powered with compressed natural gas would emit CO_2 and CO at lower levels than would either gasoline or diesel vehicles, although CH_4 emissions might be higher.

Fuel Production and Conversion

Significant quantities of greenhouse gases are emitted during the production of energy and its conversion to end-use energy forms. Several major components of these fuel production and conversion processes are discussed below.

Natural Gas Flaring, Venting, and Leaking. During the production of oil and natural gas, some portion of natural gas, which is mostly methane, is typically vented to the atmosphere (as CH_4) or flared (thereby producing CO_2) rather than produced for commercial use. Venting typically occurs during natural gas drilling and well maintenance operations to avoid pressure buildup, to test well drawdown, and during required maintenance at existing production wells. Flaring is most common in conjunction with oil production when no market can be found for the natural gas associated with oil reservoirs. In some circumstances, the gas may be vented rather than flared. On average, the amount of natural gas flared and vented amounts to about 2-3% of global natural gas production, although in some regions virtually all of the natural gas may be vented or flared, while in other regions (like the U. S.) the total amount flared or vented is less than 0.5% of total production (U.S. DOE, 1986).[9] Currently, approximately 50 teragrams (Tg) of CO_2 are released to the atmosphere from flaring of natural gas (Rotty, 1987).[10]

Leaks of natural gas also occur during the refining, transmission, and distribution of the gas. These leaks may occur at the refinery as the gas is cleaned for market, from the pipeline system during transportation to the end-user, or during liquefaction and regasification if liquified natural gas (LNG) is produced. About 20-50 Tg of CH_4 are released to the atmosphere each year from leaking and venting of natural gas (Crutzen, 1987; Cicerone and Oremland, 1989).

Coal Mining. As coal forms, CH_4 produced by the decomposition of organic material, becomes trapped in the coal seam. This CH_4 is released to the atmosphere during coal extraction operations. The amount of CH_4 released by coal mining varies depending on factors such as depth of the coal seam, quality of the coal, and characteristics of the geologic strata surrounding the seam. The amount of CH_4 emitted as a result of coal mining is highly uncertain, with estimates ranging from 25 to 45 Tg per year (Cicerone and Oremland, 1989). If coal mining operations intensify, the quantity of methane released as an indirect result of mining is expected to increase at a comparable rate.

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[9] U.S. regulations strictly govern the flaring and venting of natural gas. In other parts of the world, however, insufficient data exists to determine whether the natural gas is flared or vented, although safety precautions would strongly encourage flaring rather than venting.

[10] 1 Tg = 1 teragram = million metric tons = 10^{12} grams.

Synthetic Fuel Production. As conventional petroleum resources are depleted, some of the demand for liquid (oil and natural gas liquids) and gaseous (natural gas) fuels may be met by synthetic fuels. Although there is currently little synthetic fuel produced in the world, processes have been developed to convert relatively abundant solid energy resources such as coal, oil shale, and tar sands to liquid or gaseous products that could be consumed in the same end-use applications as conventional oil and gas.

Significant amounts of energy are typically required to produce synthetic fuels. The conversion process produces greenhouse gas emissions, particularly CO_2, so that the net emissions per unit of energy for synthetic fuels are greater than those for conventional fossil fuels. For example, the CO_2 emissions from production and consumption of synthetic liquid fuels from coal are about 1.8 times the amount from conventional liquid fuels from crude oil (Marland, 1982). Table 4-4 lists emission rates for both conventional fossil fuels and synthetic fuels produced from coal and shale oil.

Future Trends

As shown in Figure 4-4, the quantity of CO_2 emitted to the atmosphere as a result of the combustion of fossil fuels has increased dramatically in the last century. This increase in fossil-fuel-produced CO_2 emissions is the main factor that has led to an increase in atmospheric CO_2 concentrations -- from about 280 ppm in preindustrial periods to about 345 ppm today. As discussed in Chapter II, future CO_2 concentrations will depend on many factors, but most important will be

TABLE 4-4

Carbon Dioxide Emission Rates for Conventional and Synthetic Fuels

Fuel	CO_2 Emission Rate (g C/10^9J)	Notes
Conventional Fossil Fuels (rates for consumption)		
Natural Gas	13.5-14.2	
Liquid Fuels from Crude Oil	18.2-20.6	Differences are partly attributable to product mix, i.e., gasoline versus fuel oil and gasoline.
Bituminous Coal	23.7-23.9	
Synthetic Fuels (rates for production and consumption)		
Shale Oil	104.3	High temperature, 10 gal/ton shale
	66.4	High temperature, 25 gal/ton shale
	47.6	Modified in situ, 28 gal/ton shale
	28.4	Low temperature retorting
Liquids from Coal	51.3	Gasoline from methanol using Mobil MTG process
	41.8	Sasol-type technology, Eastern coal
	39.9	FHP process
	38.6	Exxon-Donor Solvent, Eastern coal
	37.2	H-coal
	31.9	Generic 75% thermal efficiency
	30.5	SRC-II, liquid and gas products
High-Btu gas from coal	40.7	Lurgi
	40.1	Hygas
	36.2	Generic 66% thermal efficiency
	32.7	Via synthesis gas with by-product credits

Source: Marland, 1982.

the rate of growth in energy demand and the type of energy that is consumed in order to satisfy this demand.

The Fossil-Fuel Supply

Higher levels of energy demand will produce higher levels of greenhouse gas emissions if the demand is satisfied with fossil fuels. As indicated above, fossil fuels currently supply a majority of the world's energy needs, and it seems likely that fossil fuels will continue to play a key role in the world's energy supply picture for decades to come. However, supplies of fossil fuels are not unlimited. Resource and reserve estimates for coal, oil, and gas are listed in Table 4-5. A resource is any presently or potentially extractable mineral supply, a reserve is a presently extractable supply. A resource that is not presently economic to extract, may become economic in the future and then be called a reserve. The estimates of the lifetimes of fossil-fuel reserves are based on current (1985) rates of production. The lifetime estimates of fossil-fuel resources are based on linear and exponential extrapolations of current energy demand (described below). Despite uncertainties about the size of the resource base and the rate at which the resource base may be depleted, it is clear from a technical standpoint that the consumption of fossil fuels could continue for a very longtime. As will be discussed in Chapter V, if the world continues to rely on fossil fuels to meet the majority of its energy needs, the amount of carbon emitted to the atmosphere may be many times greater than current levels.

Future Energy Demand

The future rate of energy demand depends on many variables, including the rate of population growth, the rate of economic growth, energy prices, the types of energy services demanded by consumers, the type and efficiency of technology used, and the type and amount of energy supplies

TABLE 4-5

Estimates of Global Fossil-Fuel Resources[a]

(Exajoules)

	Geological Resources (exajoules)	Reserves (exajoules)	Reserves/ Resources (%)	Reserves Lifetime[b] (Years)	Resource Lifetime (Years)	
					Linear Extrapolation	Exponential Extrapolation
Coal	315,800	20,400	6	229	524	103
Oil	12,800	4,300	34	41	69	39
Gas	10,100	3,700[c]	37	61	86	44

[a] Resources estimates, as of 1985, are from the World Energy Conference (1980), adjusted for global production from 1979-85. Reserve estimates are from DOE/EIA (1986): oil and gas estimates as of January 1, 1986; coal estimates as of 1981.

[b] Based on 1985 rates of production.

[c] Includes estimates for the Middle East and USSR.

Sources: World Energy Conference, 1980; United Nations, 1983, 1987; U.S. DOE, 1986.

available (Chapter V). Two hypothetical cases based on crude extrapolations illustrate potential upper and lower bounds on future energy demand (see Figure 4-7) and the lifetime of fossil fuel resources (Table 4-5). For example, from 1950 to 1973, the average annual growth rate in energy demand was 5.2%. If this rate of growth were exponentially extrapolated to 2050, global energy demand would be about 254 TW (or equivalently about 8,000 EJ), almost 30 times the 1985 level.[11] This amount of energy demand could lead to an increase in annual CO_2 emissions from the current 5.2 Pg C to about 140 Pg C in 2050, assuming that this demand is met by consumption of fossil fuels. Cumulative energy demand for 1985 through 2050 based on this extrapolation represents over five times the amount of fossil fuels in proven reserves and about 45% of the resource estimate. On the other hand, the average annual growth rate in energy demand from 1973 to 1985 was much lower: about 2.2%. If this rate were linearly extrapolated to 2050, global energy demand would be about 23 TW (720 EJ) -- almost 150% greater than the demand in 1985 -- which could increase annual CO_2 emissions from fossil fuels to nearly 13 Pg C. Cumulative energy demand for 1985 through 2050 based on the linear extrapolation represents about 115% of proven fossil fuel reserves, or nearly 10% of estimated resources.

INDUSTRIAL PROCESSES

There are three significant non-energy sources of greenhouse gases associated with industrial activity: the use of chlorofluorocarbons (CFCs), halons, and chlorocarbons (collectively, halocarbons); cement manufacture; and waste disposal in landfills. The use of CFCs, halons, and chlorocarbons, which are man-made chemicals with a variety of applications, results in their release to the atmosphere. Certain uses, such as aerosol propellants and solvents, result in instantaneous release (when the product is used), while others, such as foam-blowing agents and refrigerants, result in a

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[11] TW = Terawatt-years per year = 10^{12} watt-years per year; 1 [illegible]W = 31.53 EJ; 1 EJ = 1 Exajoule = 10^{18} joules; 1055 joules = 1 Btu.

FIGURE 4-7

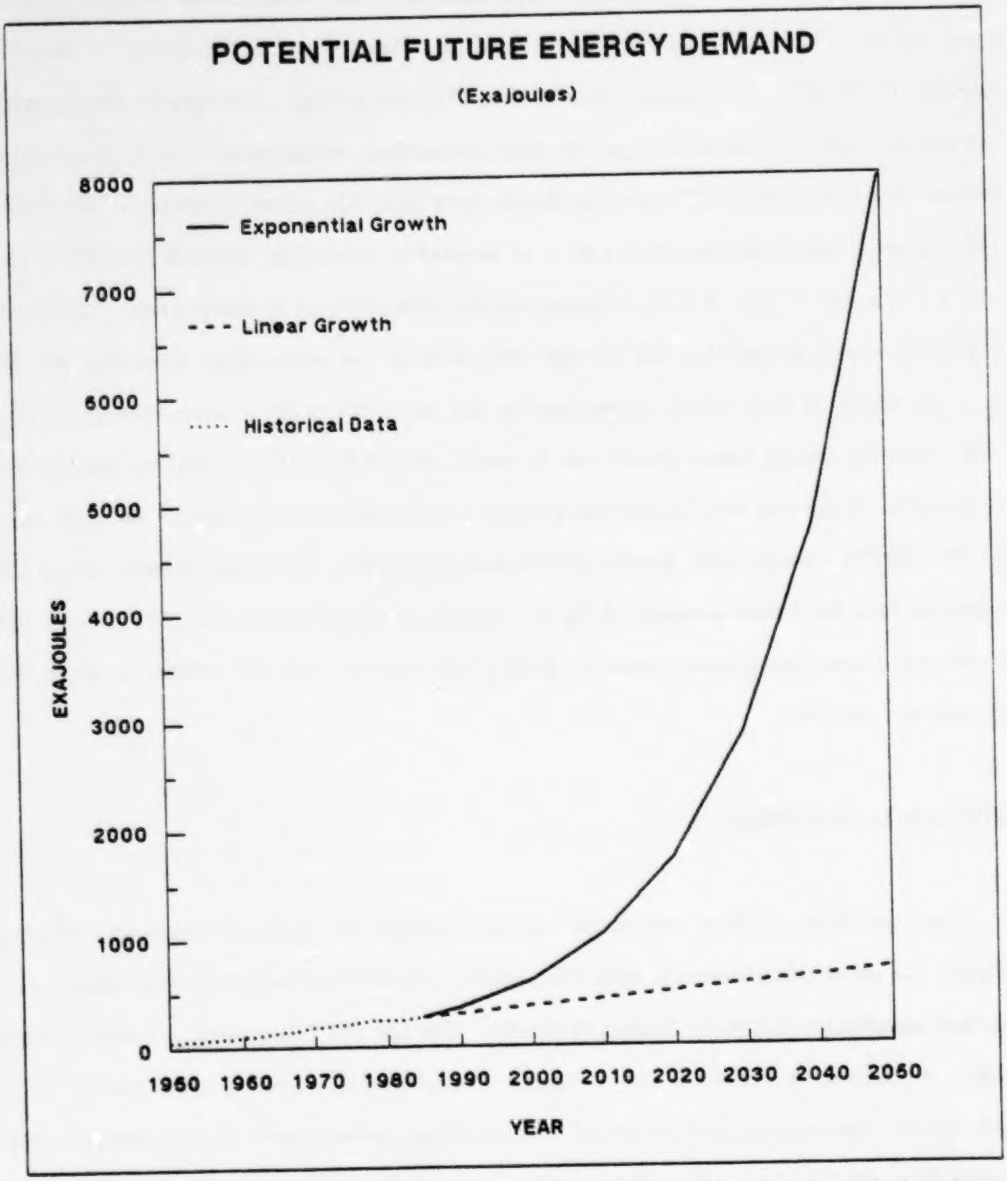

Figure 4-7. Two hypothetical cases of future energy demand. The upper case is based on an exponential extrapolation of the average annual growth rate in energy demand between 1950 and 1973, a period of rapid growth in demand. The lower case is based on a linear extrapolation of the average annual growth rate in energy demand between 1973 and 1985, when the growth rate was much lower. These two cases illustrate potential upper and lower bounds on future energy demand. (Sources for historical data: United Nations, 1976, 1982, 1983, 1987.)

delayed release. Cement manufacture results in CO_2 emissions, and waste disposal in landfills results in CO_2 and CH_4 emissions, although only the CH_4 emissions are significant in terms of the total global source.

Chlorofluorocarbons, Halons, and Chlorocarbons

Historical Development and Uses

Chlorofluorocarbons are man-made chemicals containing chlorine, fluorine, and carbon, hence the name CFCs (HCFCs contain hydrogen as well). Table 4-6 lists the major CFCs with their chemical formulae. CFCs were developed in the late 1920s in the United States as a substitute for the toxic, flammable, refrigerator coolants in use at that time. The chemicals, which are noncorrosive, nontoxic, nonflammable, and highly stable in the lower atmosphere, provided the refrigerator industry with a safe, efficient coolant that soon proved to have numerous other uses as well. Commercial development of CFCs began in 1931. During World War II, CFCs were used as propellants in pesticides against malaria-carrying mosquitos. Since then, CFCs have been used as aerosol propellants in a wide range of substances, from hairsprays to spray paints. In the 1950s, industries began using CFCs as blowing agents for plastic foam and foam insulation products. Chillers, used for cooling large commercial and industrial buildings, as well as cold storage units for produce and other perishable goods, became feasible at this time with the use of CFCs. Mobile air conditioners (in automobiles, trucks, and buses) currently constitute the largest single use of CFCs in the United States. CFCs are also used in gas sterilization of medical equipment and instruments, solvent cleaning of manufactured parts, especially electronic components and metal parts, and miscellaneous other processes and products such as liquid food freezing.

TABLE 4-6

Major Halocarbons: Statistics and Uses

Chemical	1986 Atmospheric Concentration (pptv)	Atmospheric Lifetime (Years)	Current Annual Atmospheric Concentration Growth Rates (%/yr)	Major Uses
Chlorofluorocarbons				
CFC-11 ($CFC1_3$)	226	75^{+32}_{-17}	4	Aerosols, Foams
CFC-12 (CF_2C1_2)	392	111^{289}_{-46}	4	Aerosols, Refrigeration
HCFC-22 ($CHClF_2$)	~100	20	7	Refrigeration
CFC-113 ($C_2C1_3F_3$)	30-70	90	11	Solvents
Halons (Bromofluorocarbons)				
Halon-1211 ($CBrClF_2$)	~2	25	>10	Fire extinguisher
Halon-1301 ($CBrF_3$)	~2	110	>10	Fire extinguisher
Chlorocarbons				
Carbon tetrachloride (CCl_4)	75-100	~50	1	Production of CFC-11 and CFC-12
Methylchloroform (CH_3CCl_3)	125	5.5-10	7	Solvents

Sources: U.S. EPA, 1988a; Hammitt et al., 1987; Wuebbles, 1983; WMO, 1985.

NA = No data available.

Halons, or bromofluorocarbons, are man-made chemicals containing carbon, fluorine, and chlorine and/or bromine (see Table 4-6 for the chemical formulae of the major halons in use today). These chemicals were developed in the 1970s, and are used primarily as fire extinguishants. Halon-1211 is used almost exclusively for portable (i.e., wheeled or handheld) fire extinguishers, particularly for situations where human exposure to the chemical is possible, such as in airplanes. Halon-1301 is used exclusively for total flooding fire extinguishing systems such as those used to protect computer centers, document rooms, libraries, and military installations. A summary of the 1985 end-use applications for the major CFC and halon compounds is shown in Table 4-6.

Chlorocarbons, man-made chemicals containing chlorine and carbon (see Table 4-6), are used primarily as solvents and chemical intermediates. The primary chlorocarbons are carbon tetrachloride and methylchloroform. In the United States, carbon tetrachloride was once used extensively as a solvent and grain fumigant, but because of its toxicity, only small amounts of it are used in such applications today. Its primary use in the United States is in the manufacture of CFC-11 and CFC-12, a process which consumes or destroys almost all of the carbon tetrachloride, resulting in very small emissions. However, carbon tetrachloride is believed to be used as a solvent in developing countries, resulting in considerable emissions. Methylchloroform is used worldwide as a cleaning solvent in two applications: 1) vapor degreasing (the solvent is heated and the item to be cleaned is suspended in the vapor); and 2) cold cleaning (the part to be cleaned is submerged in a tank of solvent). Small amounts are also used in adhesives, aerosols, and coatings.

Production of CFCs, halons, and chlorocarbons has grown steadily as new uses have developed. Production of the two largest CFC compounds, CFC-11 and CFC-12, increased rapidly in the 1960s and early 1970s (see Figure 4-8). Production peaked in 1974 at 812.5 gigagrams (Gg) and then declined due to a ban on most aerosol use in the United States, Canada, and Sweden in the late

FIGURE 4-8

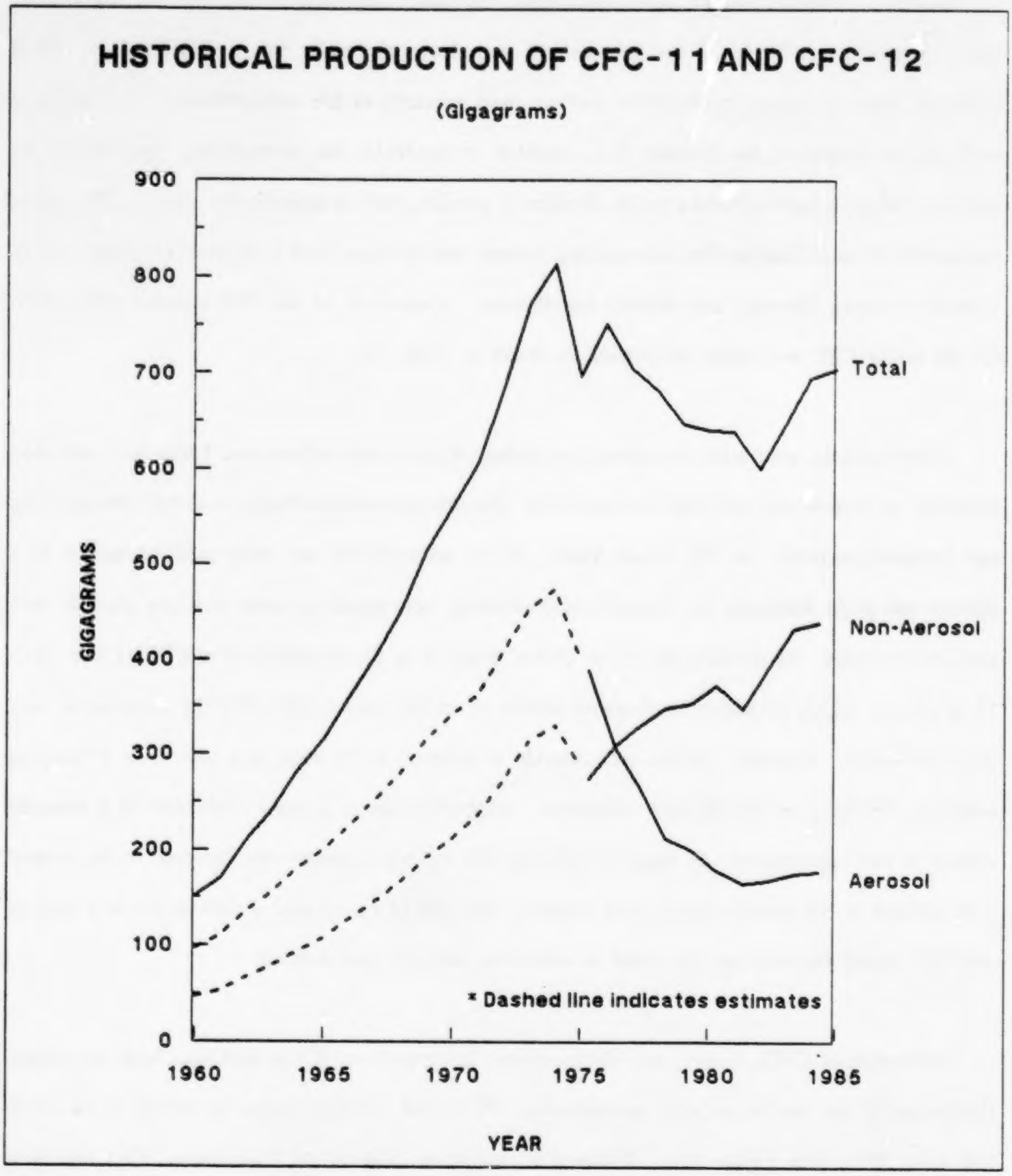

Figure 4-8. While non-aerosol production of CFC-11 and CFC-12 has grown fairly steadily since 1960, aerosol production declined in the 1970s and then leveled off in the 1980s due to a ban on most aerosol use of CFCs in the United States, Canada, and Sweden. (Source: U.S. EPA, 1987.)

1970s.[12] However, non-aerosol use has continued to grow, with 1985 production of 703.2 Gg. Globally, major CFC and halon consumption reached nearly one Tg in 1985 (see Table 4-7). Global production of carbon tetrachloride and methylchloroform in 1985 was estimated at nearly 1,029 Gg and 545 Gg, respectively (Hammitt et al., 1987).

Most CFC and halon consumption occurs in the United States and other industrialized nations. Of the 703.2 Gg of CFC-11 and CFC-12 produced in 1985, about 70% was consumed by the U.S., the EEC, and Japan (see Figure 4-9). Although CFC use is concentrated in the industrialized world, consumption has also increased recently in developing countries.

The Montreal Protocol

Concern over the effect on the Earth's atmosphere of CFCs and related anthropogenically-produced compounds containing chlorine, bromine, and nitrogen began in the 1970s. Because of their stability (i.e., their long lifetimes, see Table 4-6), CFCs are transported to the stratosphere where they contribute to the destruction of ozone. Since the early 1970s, improved understanding of this process, accumulation of data indicating growing atmospheric concentrations of CFCs, and observed depletion of stratospheric ozone, particularly in the Antarctic, have fueled international concern over this issue.

International negotiations to protect the stratosphere began in 1981 under the auspices of the United Nations Environment Programme (UNEP). These negotiations culminated in September 1987 in Montreal, Canada, where a Diplomatic Conference was held, resulting in an international agreement ("The Montreal Protocol on Substances That Deplete the Ozone Layer," or the Montreal Protocol) to begin reducing the use of CFCs and halons (chlorocarbons were not included). The

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[12] 1 Gg = 10^9 grams = 1 million kilograms.

TABLE 4-7

Estimated 1985 World Use of Potential Ozone-Depleting Substances

(gigagrams)

Chemical	World	United States	Reporting Countries	Other Communist Countries
CFC-11	341.5	75.0	225.0	41.5
CFC-12	443.7	135.0	230.0	78.7
CFC-113	163.2	73.2	85.0	5.0
Halon 1301	10.8	5.4	5.4	0.0
Halon 1211	10.8	2.7	8.1	0.0
Carbon tetrachloride	1029.0	280.0	590.0	159.0
Methylchloroform	544.6	270.0	186.7	87.0

Source: Hammit et al., 1986.

FIGURE 4-9

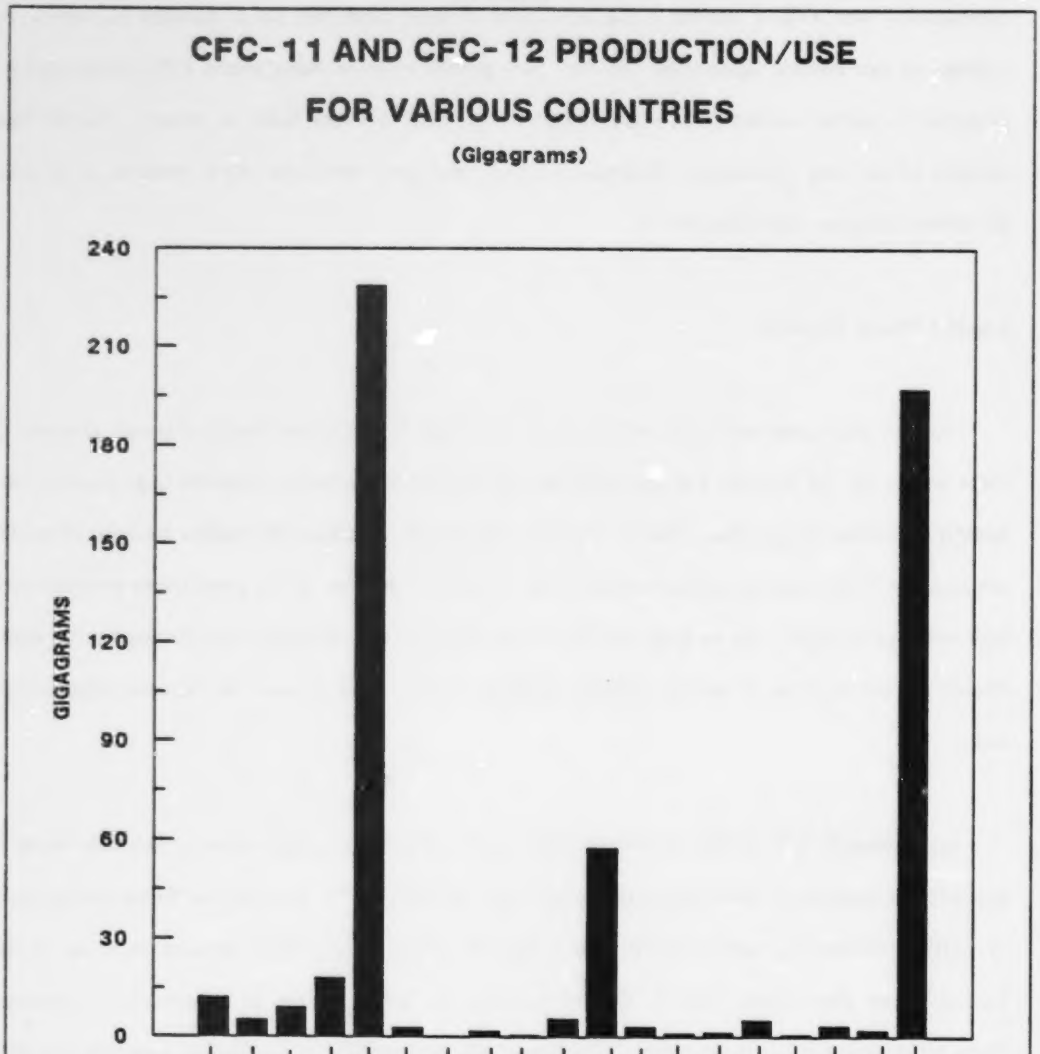

Figure 4-9. The EEC, the United States, and Japan accounted for almost 70% of the 1985 global production of CFC-11 and CFC-12. (Source: U.S. EPA, 1988a.)

Montreal Protocol came into force on January 1, 1989 and has been ratified by 31 countries, representing over 90% of current world production of these chemicals (as of January 11, 1989). As a result of this historic agreement, the very high growth rates in atmospheric CFC concentrations projected in earlier studies (e.g., Ramanathan et al., 1985) are not likely to occur. Nevertheless, because of the long atmospheric lifetimes of CFCs, their concentrations could continue to increase for several decades (see Chapter V).

Landfill Waste Disposal

Humans have generated solid wastes since they first appeared on Earth, although disposal of these wastes did not become a major problem until the rise of synthetic materials (e.g., plastics) and densely-populated urban areas. The environment can usually assimilate the smaller amounts of wastes produced by rural, sparsely-settled communities. However, because urban populations produce such high volumes of waste, due to both the sheer concentration of individuals contributing to the waste stream and the high use of heavily-packaged products, urban waste disposal has become a formidable task.

Approximately 80% of the municipal solid wastes collected in urban areas around the world is deposited in landfills or open dumps (Bingemer and Crutzen, 1987). Sanitary landfilling (compaction of wastes, followed by daily capping with a layer of clean earth), which became common in the United States after World War II, is used primarily in urban centers in industrialized countries. Open pit dumping is the most common "managed" disposal method in developing countries (30-50% of the solid wastes generated in cities of developing countries is uncollected [Cointreau, 1982]). Most landfills and many open dumps develop anaerobic conditions, resulting in decay of organic carbon to CH_4 and CO_2. The amount of CH_4 resulting from anaerobic decay of organic municipal and industrial wastes in landfills is currently about 30-70 Tg per year (Bingemer and Crutzen, 1987), approximately 10% of the total annual CH_4 source.[13]

The primary variable affecting gas generation in landfills is the composition of the refuse. Wastes high in organic material (e.g., food wastes, agricultural wastes, paper products) decompose readily, while inorganics are relatively unaffected by the decomposition process. While agriculture is the largest single source of solid wastes in the U.S. (Berry and Horton, 1974), most of these wastes are not landfilled. Increasing urbanization and demand for "convenience" items, which encourages marketing of single-serving and heavily-packaged products, has resulted in increasingly greater proportions of plastics, glass, metals, and paper products, in the waste stream. Other factors influencing gas generation include inclusion of sewage sludge (which enhances gas generation), oxygen concentration, moisture content, pH, and available nutrients.

Disposal of municipal solid waste in industrial nations increased by 5% per year during the 1960s, and by 2% per year in the 1970s (CEQ, 1982). Currently, per capita waste production in industrialized countries is considerably larger than in developing countries (see Table 4-8), and the largest contribution of landfill CH_4 comes from the industrialized world (Bingemer and Crutzen, 1987). Although current rates of waste disposal in landfills have begun to level off in many industrialized countries, associated CH_4 emissions are probably still growing because the total quantity of waste in place is still increasing. In the developing world, with its high population growth rates and increasing urbanization, municipal solid waste disposal is projected to double by the year 2000 (Kresse and Ringeltaube, 1982), so CH_4 production from waste dumps and/or sanitary landfills can be expected to increase rapidly in developing countries.

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[13] This estimate does not include methane from anaerobic decomposition of agricultural wastes, which could be a significant quantity. The total amount of carbon in agricultural wastes in the United States alone is already 2.5 times larger than the 113 million metric tons of waste carbon that are generated and dumped in landfills worldwide (Bingemer and Crutzen, 1987).

TABLE 4-8

Refuse Generation Rates in Selected Cities

City	Per Capita Waste Generation Rate (kg Per Day)
Industrial Cities	
New York, United States	1.80
Singapore	0.87
Hong Kong	0.85
Hamburg, West Germany	0.85
Rome, Italy	0.69
Developing Cities	
Jakarta, Indonesia	0.60
Lahore, Pakistan	0.60
Tunis, Tunisia	0.56
Bandung, Indonesia	0.55
Medellin, Colombia	0.54
Surabaya, Indonesia	0.52
Calcutta, India	0.51
Cairo, Egypt	0.50
Karachi, Pakistan	0.50
Manila, Philippines	0.50
Kanpur, India	0.50
Kano, Nigeria	0.46

Source: Cointreau, 1982.

Cement Manufacture

Cement manufacture produces CO_2, as well as numerous other exhaust gases. As demand for cement has grown over the last century, CO_2 emissions associated with this industry have increased from 18 to 134 Tg C between 1950 and 1985 (see Figure 4-10). In recent years CO_2 emissions from cement production have grown at a faster rate than those from fossil fuel combustion: In the early 1950s CO_2 emitted as a result of cement manufacture was approximately 1% of the amount emitted from the consumption of fossil fuels; by the early 1980s this fraction had increased to 2.5% (Rotty, 1987).

The CO_2 emissions resulting from cement manufacture occur during the production of clinker, a material produced midway through the process. After the raw materials (cement rock, limestone, clay, and shale) are quarried and crushed, they are ground and blended to a mixture that is approximately 80% limestone by weight. The mixture is then fed into a kiln for firing, where it is exposed to progressively higher temperatures that cause heating, then drying, calcining, and sintering. Finally, the feed is heated to the point of fusion (approximately 1595°C), and clinker (round, marble-sized particles) is produced. It is during the calcination process, which occurs at approximately 900 to 1000°C, that the limestone ($CaCO_3$) is converted to lime (CaO) and CO_2, and the CO_2 is released. For every million tons of cement produced, approximately 0.137 Tg C as CO_2 is emitted from calcining (Rotty, 1987).[14] An additional 0.165 Tg C is emitted per million ton of cement produced from fossil fuel used for kiln firing and electricity. This CO_2 is accounted for as part of industrial energy use emissions.

World cement production has increased at an average annual rate of approximately 6% since the 1950s, from 133 million tons in 1950 to 972 million tons in 1985 (U.S. BOM, 1949-1986). Cement

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[14] 1 ton = 1 metric ton = 1000 kg.

FIGURE 4-10

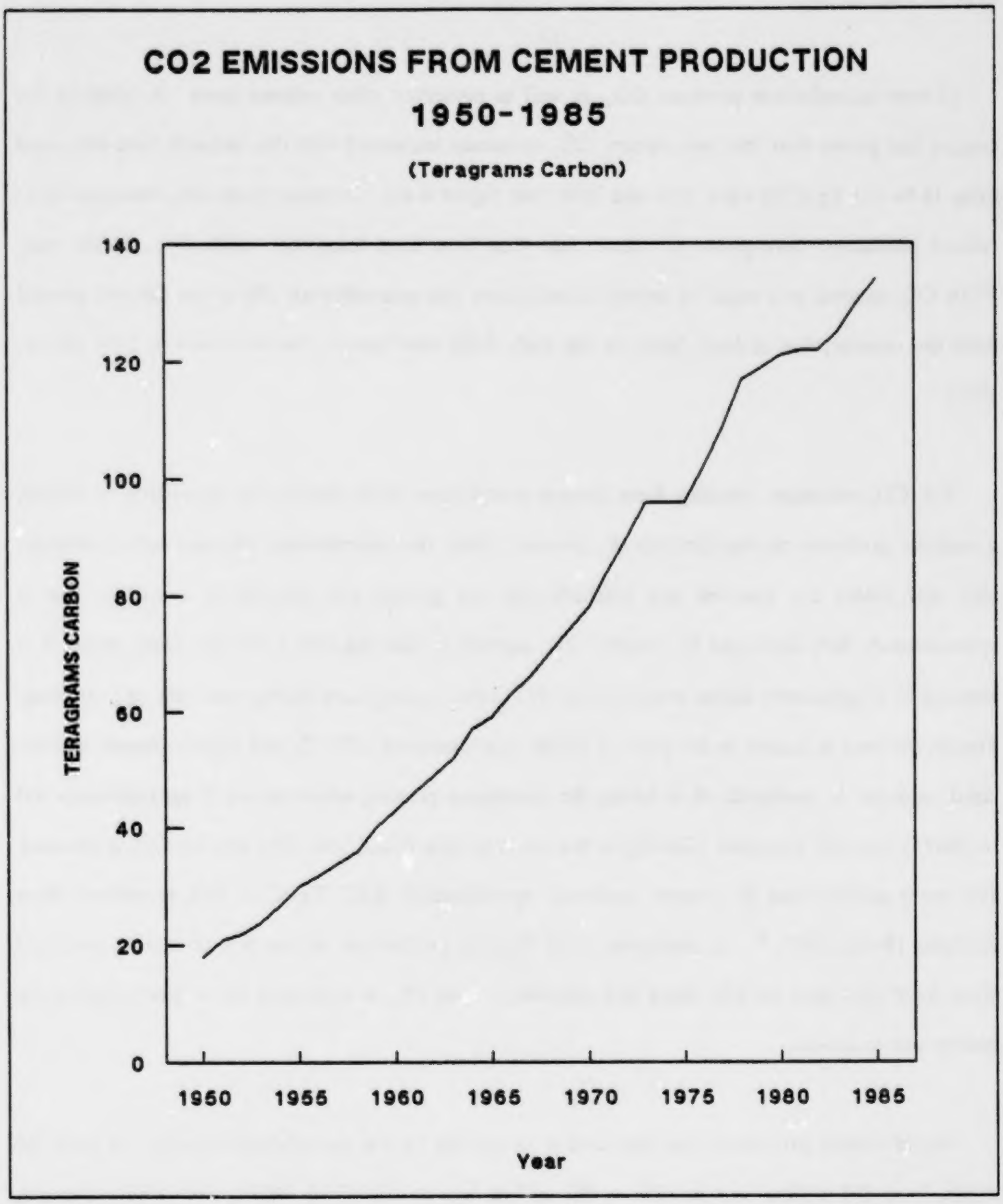

Figure 4-10. Carbon dioxide emissions from cement production grew from 18 to 134 Tg between 1950 and 1985, an average annual rate of growth of about 6%. (Sources: Rotty, 1987; U.S. BOM, 1986.)

production growth rates in individual countries have varied during this period (see Figure 4-11) due to economic fluctuations in cement's primary market, i.e., the construction industry, and competitive shifts internationally among the primary cement-producing countries. For example, in 1951 the United States produced approximately 28% of the global total, while by 1985 its share had shrunk to 7%.[15] During the same time, the production shares for the USSR grew from 8% to 13%, for China, from less than 1% to 15%, and for Japan, from 4% to 8%. Although many national markets, except the United States', experienced low levels of demand during the 1980s, global cement production is expected to continue to grow faster than the GNP for some time.

LAND USE CHANGE

Over the past few centuries, man has significantly changed the surface of the Earth. Forests have been cleared, wetlands have been drained, and agricultural lands have been expanded. All of these activities have resulted in considerable changes in trace gas emissions to the atmosphere. Deforestation results in a net release of carbon from both the biota and the soils (unless the land is reforested) as these organic carbon pools burn or are decomposed. Biomass burning, due to shifting agriculture, burning of savanna, use of industrial wood and fuelwood, and burning of agricultural wastes, is a source of CO_2, as well as CH_4, N_2O, and NO_x. [16] Destruction of wetlands, from either filling or dredging, can alter the atmospheric CH_4 budget, since anaerobic decomposition in wetlands produces CH_4.

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[15] The U.S. is currently a net importer of cement; the volume of its imports has grown, representing only a few percent of consumption in the early 1980s but as much as 18 percent in 1986 (International Trade Administration, 1987).

[16] Shifting agriculture is the practice of clearing and planting a new area, farming it until productivity declines, and then moving on to a new plot to start the cycle over again. If the land is allowed to reforest, there are no net CO_2 emissions.

FIGURE 4-11

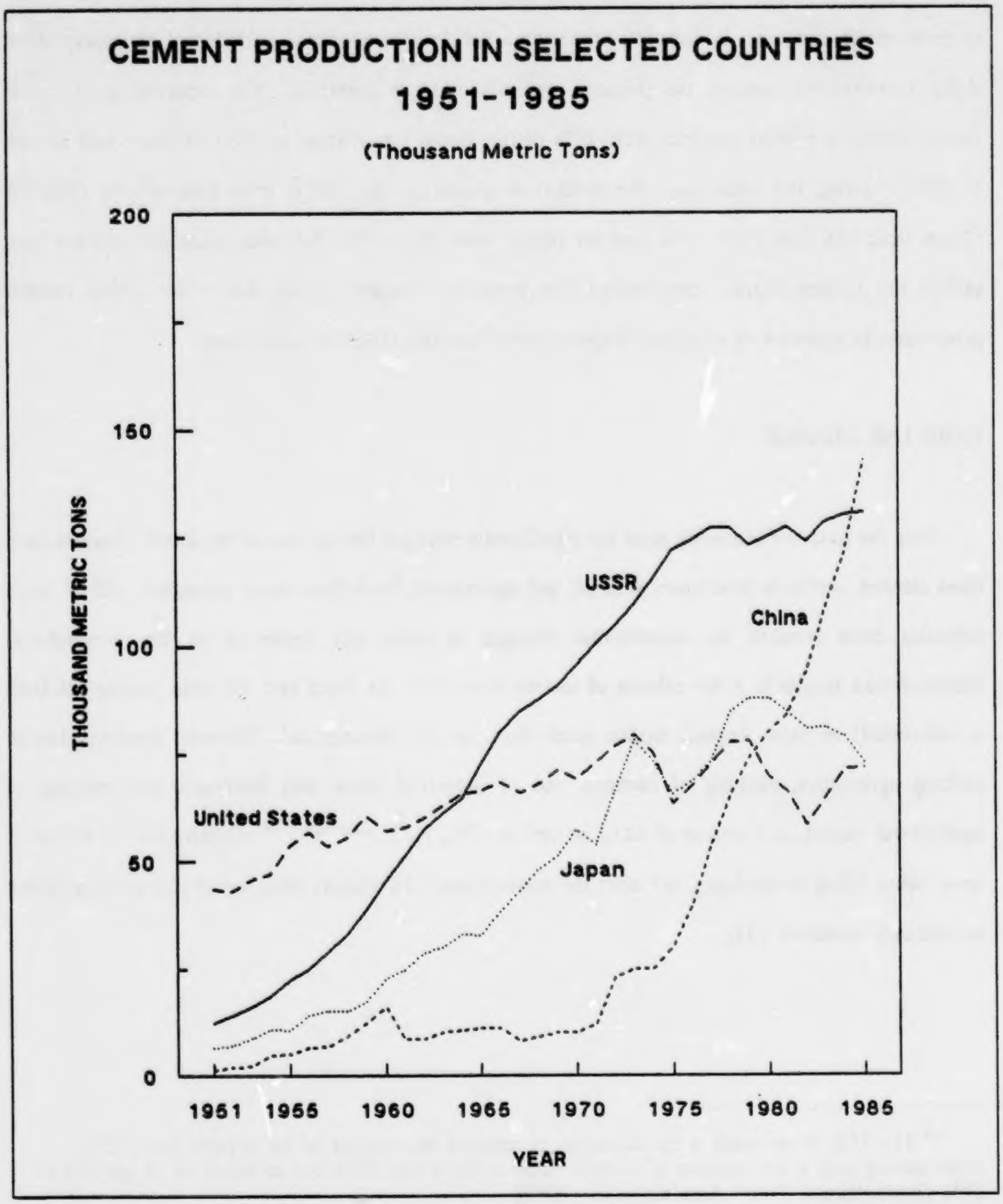

Figure 4-11. World cement production grew at an average annual rate of about 6% between 1950 and 1985. Growth has been particularly rapid in China, the U.S.S.R., and Japan. (Source: U.S. BOM, selected years.)

Deforestation

Estimates of net emissions of CO_2 to the atmosphere due to changes in land use (deforestation, reforestation, logging, and changes in agricultural area) in 1980 range from 0.4 to 2.6 Pg C (Houghton et al., 1987; Detwiler and Hall, 1988), which accounts for approximately 10-30% of annual anthropogenic CO_2 emissions to the atmosphere. Deforestation in the tropics accounted for almost all of the flux; the carbon budget of temperate and boreal regions of the world has been approximately in balance in recent years. Of the net release of carbon from tropical deforestation, 55% was produced by only six countries in 1980: Brazil, Indonesia, Columbia, the Ivory Coast, Thailand, and Laos (see Figure 4-12).

The world's forest and woodland areas have been reduced 15% since 1850, primarily to accommodate the expansion of cultivated lands (IIED and WRI, 1987). The largest changes in forest area during this period have occurred in Africa, Asia, and Latin America. Europe is the only region that has experienced a net increase in forest area over this time interval. Forest area began to increase in Europe in the 1950s and in North America in the 1960s (see Table 4-9). However, recent data from the Food and Agriculture Organization of the United Nations (FAO) and the U.S. Forest Service indicates that net deforestation may be occurring in the United States -- although there are discrepancies between the two data sets. The FAO data indicates that between 1980 and 1985 the area of U.S. forest and woodlands decreased by approximately 3.8 million hectares (million ha) per year, or 1.4% per year (FAO, 1986b).[17] The U.S. Forest Service (Alig, 1988) estimates that between 1977 and 1987 the area of U.S. forests decreased by approximately 0.41 million ha per year, or 0.14% per year.

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[17] 1 ha = 1 hectare = 2.471 acres.

FIGURE 4-12

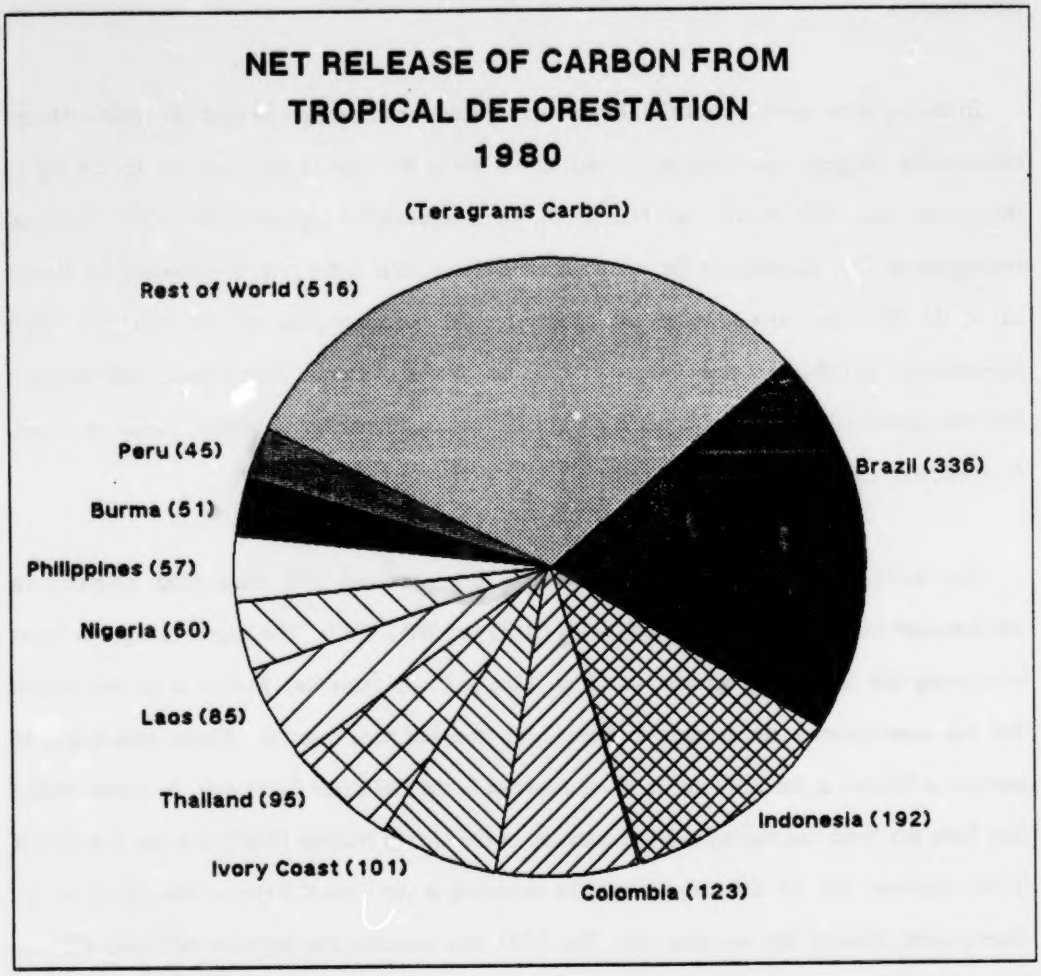

Figure 4-12. Tropical deforestation accounts for approximately 10-30% of the annual anthropogenic CO_2 emissions to the atmosphere. Over half of the 1980 CO_2 emissions from deforestation was produced by six countries: Brazil, Indonesia, Columbia, the Ivory Coast, Thailand, and Laos. (Source: Houghton et al., 1987.)

TABLE 4-9

Land Use: 1850-1980

	Area (million hectares)														Percentage Change 1850 to 1980
	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980	
TEN REGIONS															
Forests and Woodlands	5,919	5,898	5,869	5,833	5,793	5,749	5,696	5,634	5,553	5,455	5,345	5,219	5,103	5,007	-15
Grassland and Pasture	6,350	6,340	6,329	6,315	6,301	6,284	6,269	6,260	6,255	6,266	6,293	6,310	6,308	6,299	-1
Croplands	538	569	608	659	712	773	842	913	999	1,085	1,169	1,278	1,396	1,501	179
Tropical Africa															
Forests and Woodlands	1,336	1,333	1,329	1,323	1,315	1,396	1,293	1,275	1,251	1,222	1,188	1,146	1,106	1,074	-20
Grassland and Pasture	1,061	1,062	1,064	1,067	1,070	1,075	1,081	1,091	1,101	1,114	1,130	1,147	1,157	1,158	9
Croplands	57	58	61	64	68	73	80	88	101	118	136	161	190	222	288
North Africa and Middle East															
Forests and Woodlands	34	34	33	32	31	30	28	27	24	21	18	17	15	14	-60
Grassland and Pasture	1,119	1,119	1,118	1,117	1,116	1,115	1,113	1,112	1,108	1,103	1,097	1,085	1,073	1,060	-5
Croplands	27	28	30	32	35	37	40	43	49	57	66	79	93	107	294
North America															
Forests and Woodlands	971	968	965	962	959	954	949	944	941	940	939	939	941	942	-3
Grassland and Pasture	571	559	547	535	522	504	486	468	454	450	446	446	447	447	-22
Croplands	50	65	80	95	110	133	156	179	196	201	206	205	204	203	309
Latin America															
Forests and Woodlands	1,420	1,417	1,414	1,408	1,401	1,394	1,383	1,369	1,348	1,316	1,273	1,225	1,186	1,151	-19
Grassland and Pasture	621	623	625	627	630	634	638	646	655	673	700	730	751	767	23
Croplands	18	19	21	24	28	33	39	45	57	72	87	104	123	142	677
China															
Forests and Woodlands	96	93	91	89	86	84	82	79	76	73	69	64	59	58	-39
Grassland and Pasture	799	799	798	796	797	797	797	796	796	794	793	789	784	778	-3
Croplands	75	78	81	84	86	89	91	95	96	103	108	117	127	134	79
South Asia															
Forests and Woodlands	317	315	311	307	303	299	294	289	279	265	251	235	210	180	-43
Grassland and Pasture	189	189	189	189	189	189	190	190	190	190	190	190	189	187	-1
Croplands	71	73	77	81	85	89	93	98	108	122	136	153	178	210	196
Southeast Asia															
Forests and Woodlands	252	252	251	251	250	249	248	247	246	244	242	240	238	235	-7
Grassland and Pasture	123	123	122	121	119	118	116	114	111	108	105	102	97	92	-25
Croplands	7	7	8	10	12	15	18	21	25	30	35	40	47	55	670
Europe															
Forests and Woodlands	169	158	157	157	156	156	155	155	155	154	154	156	161	167	4
Grassland and Pasture	150	147	145	144	143	142	141	139	138	137	136	136	137	138	-8
Croplands	132	136	140	142	143	145	146	147	149	150	152	151	145	137	4
USSR															
Forests and Woodlands	1,067	1,060	1,052	1,040	1,027	1,014	1,001	987	973	961	952	945	940	941	-12
Grassland and Pasture	1,078	1,081	1,083	1,081	1,079	1,078	1,076	1,074	1,072	1,070	1,070	1,069	1,065	1,065	-1
Croplands	94	98	103	118	132	147	162	178	194	208	216	225	233	233	147
Pacific Developed Countries															
Forests and Woodlands	267	267	266	265	264	263	262	261	260	259	258	252	247	246	-8
Grassland and Pasture	638	638	638	637	635	634	632	630	629	627	625	617	609	608	-5
Croplands	6	6	7	9	12	14	17	19	22	24	28	42	56	58	841

Source: IIED and WRI, 1987.

Currently, it is estimated that approximately 11.3 million ha of tropical forests are lost each year, while only 1.1 million ha are reforested per year (FAO, 1985). Most of the tropical deforestation is due to transfer of forest land to agricultural use, through shifting agriculture and conversion to pasture. FAO has estimated a demand for an additional 113-150 million ha of cultivated land for the 20-year period between 1980 and 2000 to meet food production needs (FAO, 1981). Most of this land will have to come from areas that were once forested, however there is a large potential to use land currently under shifting cultivation by adapting low-input agricultural techniques (Chapter VII). Fuelwood use also contributes to deforestation, particularly in Africa where fuelwood is a major source of residential energy. Sixty-three percent of the total energy consumption of developing African countries, 17% in the Asian countries, and 16% in the Latin American countries, is provided by fuelwood. In the Sudan, Senegal, and Niger, fuelwood provides 94, 95, and 99%, respectively, of household energy consumption (Anderson and Fishwick, 1984). Rapidly-increasing populations, particularly in developing nations, will result in increasing demands on forest lands to meet growing agricultural and energy needs.

Biomass Burning

Biomass burning, in addition to contributing to the atmospheric CO_2 budget, contributes approximately 10-20% of total annual CH_4 emissions, 5-15% of the N_2O emissions, 10-35% of the NO_x emissions, and 20-40% of the CO emissions (Crutzen et al., 1979; WMO, 1985; Logan, 1983; Stevens and Engelkemeir, 1988; and Andreae et al., 1988). These estimates are for instantaneous emissions from combustion. Recent research has shown that biomass burning also results in longer-term (at least up to 6 months after the burn) emissions of NO and N_2O due to enhancement of biogenic soil emissions (Anderson et al., 1988). Estimates of emissions of trace gases due to biomass burning are very uncertain for two reasons: 1) data on amounts and types of biomass burned are scarce, and 2) emissions per unit of biomass burned are highly variable.

Activities associated with biomass burning include agriculture, colonization, wildfires and prescribed fires, and burning of industrial wood and fuelwood. Currently, agricultural burning, due to shifting agriculture and burning of agricultural wastes is estimated to account for over 50% of the biomass burned annually (Table 4-10). Biomass burning is a particularly important source of trace-gas emissions in the tropics, where forest exploitation is unsurpassed. Continued rapid population growth and exploitation of forests may substantially increase emissions from biomass burning in the future.

Wetland Loss

Annual global emissions of CH_4 from freshwater wetlands are estimated to be 110 Tg, approximately 25% of the total annual source of 400 to 600 Tg (Matthews and Fung, 1987). Of the approximately 530 million ha producing this CH_4, 39% is forested bog, 17% is nonforested bog, 21% is forested swamp, 19% nonforested swamp, and 4% alluvial formations.[18] The bulk of the bog acreage is located between 40°N and 70°N, while swamps predominate between 10°N and 30°S. Alluvial formations are concentrated between 10°N and 40°S (see Figure 4-13). Coastal saltwater and brackish water environments produce minor amounts of CH_4 in comparison, probably due to the inhibitory effects of dissolved sulfate (SO_4) in the interstitial water of salt-marsh sediments (DeLaune et al., 1983; Bartlett et al., 1985).

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[18] Bogs are peat- or organic-rich systems, usually associated with waterlogging and seasonal freeze-thaw cycles; swamps are low-organic formations occurring most commonly in the tropics, and alluvial formations are low-organic riverine formations.

TABLE 4-10

Summary Data on Area and Biomass Burned

Activity	Burned and/or Cleared Area (million ha)	Burned Biomass (100 Tg dry matter)
Burning due to shifting agriculture	21-62 (41)	9-25 (17)
Deforestation due to population increase and colonization	8.8-15.1 (12.0)	5.5-8.8 (7.2)
Burning of savanna and brushland	(600)	4.8-19 (11.9)
Wildfires in temperate and boreal forests	4.0-6.5 (5.4)	1.9-3.2 (2.6)
Prescribed fires in temperate forests	2.0-3.0 (2.5)	0.1-0.2 (0.2)
Burning of industrial wood and fuelwood		10-11 (10.5)
Burning of agricultural wastes		17-21 (19)
TOTAL	630-690 (660)	48-88 (68)

Data in parentheses represent average values.

Source: Crutzen et al., 1979.

FIGURE 4-13

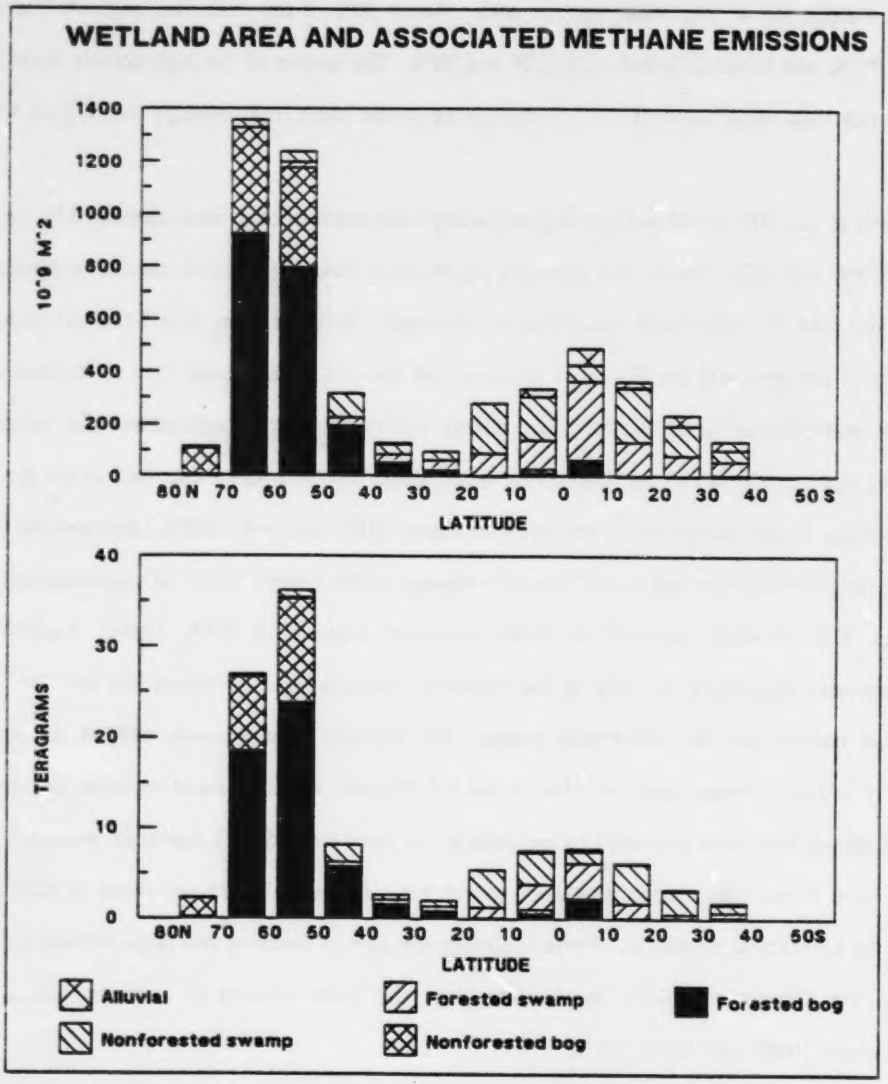

Figure 4-13. Estimated latitudinal distribution of wetland area (top) and associated methane emissions (bottom). Forested and non-forested bogs located between 40° and 70°N account for approximately 50% of the current CH_4 emissions from wetlands. (Source: Matthews and Fung, 1987.)

The latitudinal distribution of wetland CH_4 emissions is estimated to be very similar to the latitudinal distribution of freshwater wetland area. About 50% of the emissions originate between 50°N and 70°N, and about 25% between 20°N and 30°S. The source of the high-latitude emissions is organic-rich bogs, while most of the low-latitude emissions come from swamps (see Figure 4-13).

Between 25 and 50% of the world's original swamps and marshes have been eliminated by human activities (IIED and WRI, 1987). For centuries people have drained and filled marshes and swamps to create dry land for agricultural and urban development. Wetland areas have been converted to open water by dredging and installation of flood-control levees, and have been used as disposal sites for dredge materials and solid wastes. Peat mining and pollution from agricultural and industrial runoff have also contributed to the destruction of wetlands. By 1970, more than half of the original wetland acreage in the United States had been destroyed (IIED and WRI, 1987). Between the mid-1950s and mid-1970s, there was a net loss of wetlands in the United States of approximately 4.6 million ha, 97% of which occurred in inland freshwater areas (U.S. OTA, 1984). Agricultural conversions were responsible for 80% of this freshwater wetland loss.[19] Wetland loss has also been extensive in Europe and the Asia-Pacific region. For example, approximately 40% of the coastal wetlands of Brittany, France, have been lost in the last 20 years, and 8100 ha of wetlands on the east coast of England have been converted to agricultural use since the 1950s. Large-scale wetland losses have not been as prevalent in the developing world, but rising populations will result in increasing demands for agricultural expansion. There is already pressure to develope two large wetland systems in Africa, the Okavango Swamps of Botswana and the Sudd Swamps of southern Sudan, for agricultural use (IIED and WRI, 1987).

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[19] For example, drainage of prairie potholes in Iowa to provide new farmland has resulted in the reduction of Iowa's original wetlands by over 98%, from 930,000 ha when settlement began, to 10,715 ha today.

AGRICULTURAL ACTIVITIES

Three agricultural activities contribute directly to atmospheric emissions of greenhouse gases: enteric fermentation in domestic animals, rice cultivation, and use of nitrogenous fertilizer. Global demand for food and agricultural products has more than doubled since 1950, fueled by rising populations and incomes. Agricultural advancements during the post-war years, such as the "Green Revolution," brought improvements in soil management and disease control, new high-yielding varieties of crops, increased application of commercial fertilizers, and increased use of machinery. Between 1950 and 1986, world grain production increased from 624 to 1,661 million tons and average yield more than doubled, from 1.1 to 2.3 tons per ha (Wolf, 1987). Over this same time interval, growth of various domestic animal populations ranged from 20 to 150% (Crutzen et al., 1986) and fertilizer consumption grew approximately 750% (Herdt and Stangel, 1984). According to projections by the Food and Agriculture Organization of the United Nations, by the year 2000, a world population of about 6 billion will require an agricultural output approximately 50 to 60% greater than that required in 1980 (FAO, 1981).

Enteric Fermentation In Domestic Animals

Methane is produced as a by-product of enteric fermentation in herbivores, a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream. Both ruminant animals (e.g., cattle, dairy cows, sheep, buffalo, and goats) and some non-ruminant animals (e.g., pigs and horses) produce CH_4. The highest CH_4 losses are reported for ruminants (approximately 4-9% of total energy intake), which are able to digest cellulose due to the presence of specific microorganisms in their digestive tracts. The amount of CH_4 that is released from both ruminant and non-ruminant animals depends on the type, age, and weight of the animal, the quality and quantity of feed, and the energy expenditure of the animal.

Of the annual global source of 400-600 Tg CH_4, domestic animals contribute approximately 65-85 Tg (Crutzen et al., 1986; Lerner et al., 1988). Domestic animals that produce the bulk of the CH_4 are (in decreasing order of amount produced) cattle, dairy cows, buffalo, goats, sheep, camels, pigs, and horses. Currently, approximately 57% comes from cattle, and 19% from dairy cows. Domestic animals in six countries, India, the USSR, Brazil, the U.S., China, and Argentina, produce over 50% of the methane by enteric fermentation (Lerner et al., 1988).

The domestic animal population has increased considerably during the last century. Between the early 1940s and 1960s, increases in global bovine and sheep populations averaged 2% per year. Since the 1960s, the rates of increase have slowed somewhat, to 1.2% and 0.6% per year, respectively (see Figure 4-14). The annual increases in global populations of pigs, buffalo, goats, and camels since the 1960s have been comparable: 1.4%, 1%, 1.2%, and 0.5%, respectively. The horse population declined about 0.25% per year. For comparison, the average annual increase in global human population since the 1960s has been about 1.8%.

Rice Cultivation

Anaerobic decomposition in flooded rice fields produces methane, which escapes to the atmosphere by ebullition (bubbling) up through the water column, diffusion across the water/air interface, and transport through the rice plants. Research suggests that the amount of CH_4 released to the atmosphere is a function of rice species, number and duration of harvests, temperature,

FIGURE 4-14

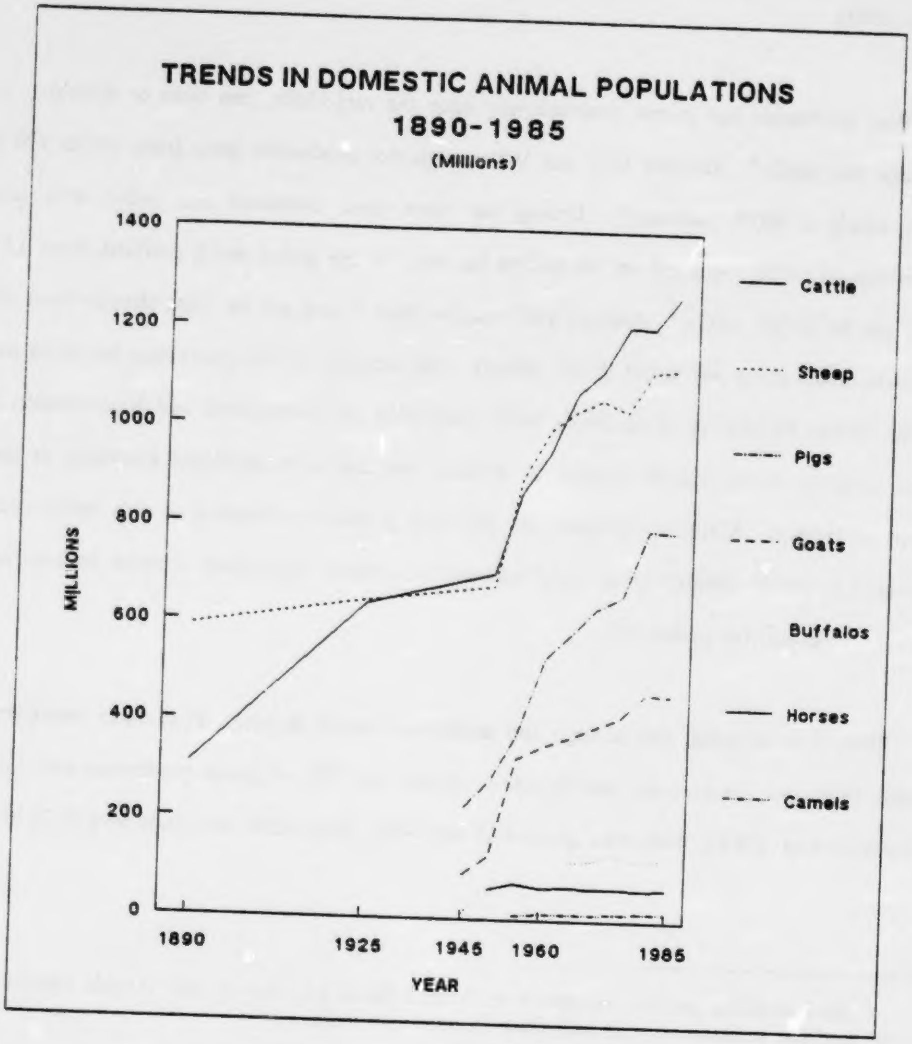

Figure 4-14. Global domestic animal populations have grown by about 0.5 to 2.0% per year during the last century. Currently, domestic animals account for about 15% of the annual anthropogenic CH_4 emissions. Note: The cattle population figures include dairy cows. (Sources: Crutzen et al., 1986; FAO, 1971, 1982, 1986a.)

irrigation practices, and fertilizer use (Holzapfel-Pschorn and Seiler, 1986; Seiler et al., 1984; Cicerone et al., 1983).

Rice cultivation has grown tremendously since the mid-1900s, due both to increases in crop acreage and yields.[20] Between 1950 and 1984, rough rice production grew from 163 to 470 million tons, nearly a 200% increase.[21] During the same time, harvested rice paddy area increased approximately 40%, from 103 to 148 million ha, and average global yields doubled, from 1.6 to 3.2 tons per ha (IRRI, 1985).[22] Average yields higher than 5 tons per ha have already been obtained in parts of the developed world (FAO, 1986a). The increase in rice production has been due both to the "Green Revolution" of the 1960s, which resulted in the development and dissemination of high-yield varieties of rice and an increase in fertilizer use, and to a significant expansion of land area under cultivation. Methane emissions are probably primarily a function of area under cultivation, rather than yield, although yield could influence emissions, particularly if more organic matter is incorporated into the paddy soil.

Over 90% of global rice acreage and production occurs in Asia. Five Asian countries, China, India, Indonesia, Bangladesh, and Thailand, account for 75% of global production and 73% of the harvested area (IRRI, 1986; see Figures 4-15 and 4-16). Rice fields contribute 60-170 Tg of methane

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[20] Rice statistics are for rice grown in flooded fields, i.e., they do not include upland rice, since methane emissions result only from flooded rice fields.

[21] Rough rice, also called paddy rice, is rice with the hull, or husk, attached. The hull contributes about 20% of the weight of rough rice. The kernel remaining after the hull is removed is brown rice. Milling of brown rice, which removes the bran, followed by polishing, results in white rice.

[22] Harvested area is the area under cultivation multiplied by the number of crops per year. For example, 1 ha that is triple-cropped is counted as 3 ha of harvested area.

FIGURE 4-15

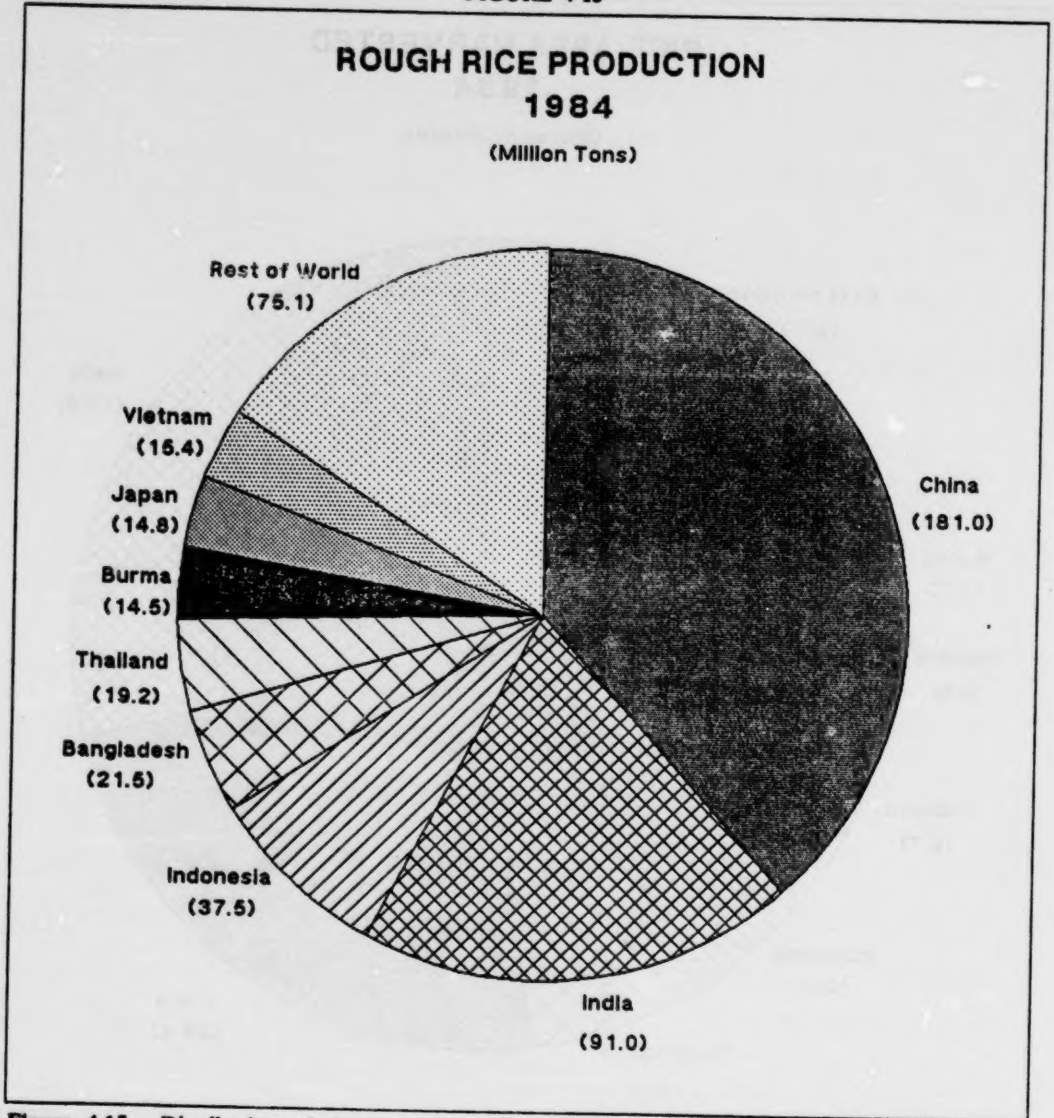

Figure 4-15. Distribution of the total rough rice production of 470 million tons. Five Asian countries, China, India, Indonesia, Bangladesh, and Thailand, accounted for approximately 75% of the 1984 global rice production. (Source: IRRI, 1986.)

FIGURE 4-16

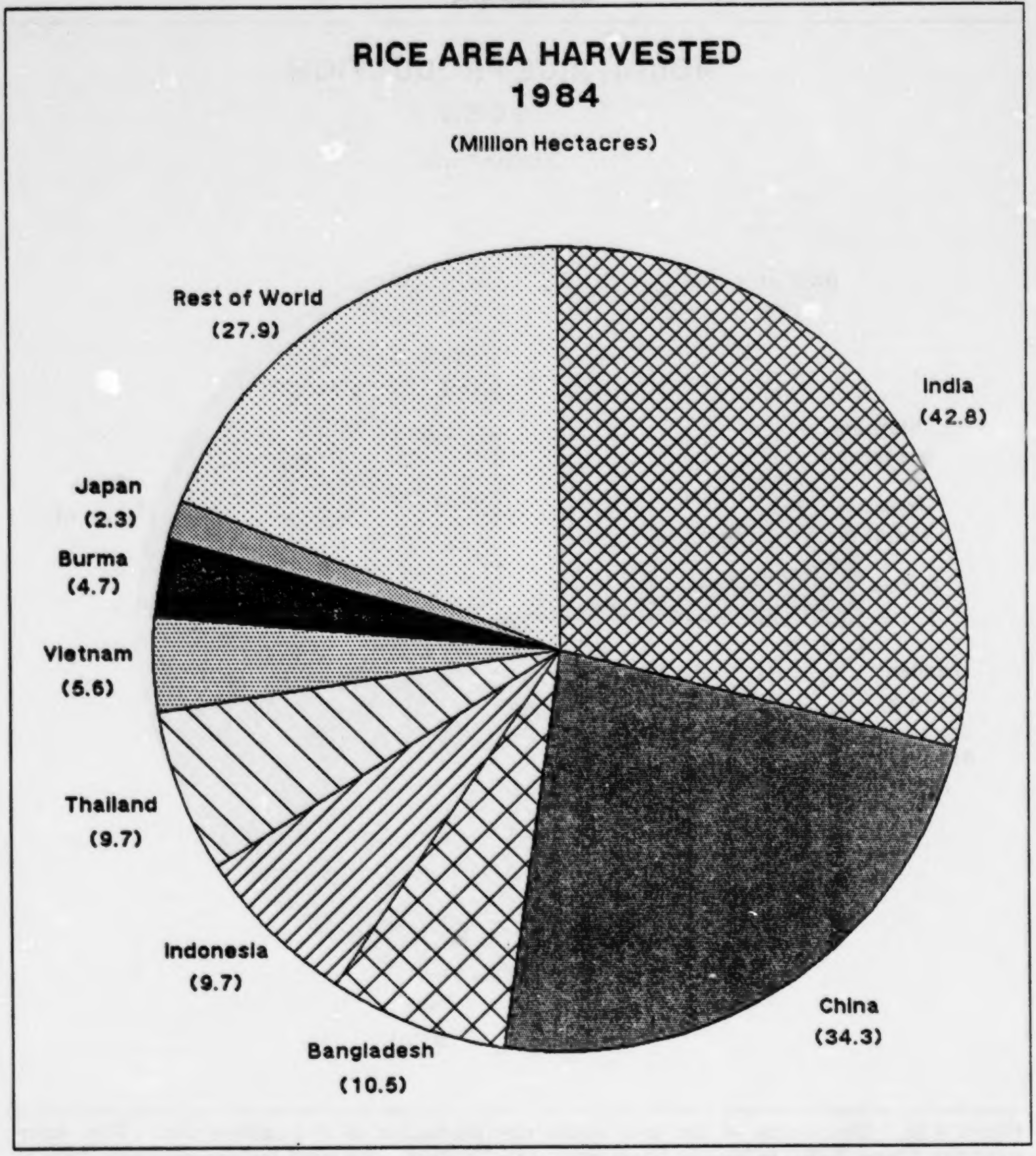

Figure 4-16. Distribution of the total harvested rice paddy area of 148 million ha. Five Asian countries, India, China, Bangladesh, Indonesia and Thailand accounted for 73% of the 1984 rice acreage harvested. (Source: IRRI, 1986.)

per year to the atmosphere, or approximately 20% of the global flux (Cicerone and Oremland, 1989). This estimate is highly uncertain because there have been no comprehensive rice-paddy flux measurements in the major rice-producing countries in Asia.

Use of Nitrogenous Fertilizer

Nitrous oxide is released through microbial processes in soils, both through denitrification and nitrification. Nitrogenous fertilizer application enhances N_2O flux rates, since some of the applied fixed N is converted to N_2O and released to the atmosphere. The amount of N_2O released depends on rainfall, temperature, the type of fertilizer applied, mode of application, and soil conditions.

Nitrogen is currently the most abundant commercial fertilizer nutrient consumed worldwide. Its dominance in the fertilizer markets has increased steadily over the last few decades, from 28% of total nutrients (nitrogen, phosphorus, and potassium) in 1950 to 64% in 1981 (Herdt and Stangel, 1984). Approximately 70.5 million tons N was consumed worldwide in 1984/1985 in the form of nitrogenous fertilizers (FAO, 1987). A preliminary estimate suggests that this produced N_2O emissions of 0.14-2.4 Tg N of the global source of approximately 8-22 Tg N per year (Fung et al., 1988) although this estimate is highly uncertain. Experiments to determine the fraction of fertilizer nitrogen lost to the atmosphere as nitrous oxide have shown a wide range of results (see Table 4-11, and Chapter II). Anhydrous ammonia, which requires sophisticated equipment for application (it is injected under pressure into the soil), is used exclusively in the United States. It comprises about 38% of the U.S. nitrogenous fertilizer consumption. Urea, which is usually broadcast as pellets by hand, comprises about 69% and 58% of nitrogenous fertilizer consumption in Asia and South America, respectively.

TABLE 4-11

Nitrous Oxide Emissions by Fertilizer Type

Fertilizer Type	Percent of Nitrogenous Fertilizer Evolved as N_2O
Anhydrous Ammonia	0.5 to 6.84
Ammonium Nitrate	0.04 to 1.71
Ammonium Type	0.025 to 0.1
Urea	0.067 to 0.5
Nitrate	0.001 to 0.50

Source: Eichner, 1988; Galbally, 1985.

Asia, Western Europe, Eastern Europe, and North America consume the major share of the world's nitrogenous fertilizers (collectively, about 85%). China, the Soviet Union, and the United States together account for approximately one-half of the world's fertilizer consumption. The twelve largest nitrogen fertilizer consumers, all of which consume more than one million tons N annually, are (in decreasing order): China, the United States, the Soviet Union, India, France, the United Kingdom, West Germany, Canada, Indonesia, Poland, Mexico, and Italy (see Figure 4-17). Together, these twelve countries account for approximately 74% of the annual nitrogenous fertilizer consumption.

Although developed nations will probably increase their consumption of commercial fertilizer over the next few decades, most of the increased demand will occur in developing nations. The World Bank estimates that over 90 million tons N will be consumed in 1997/98, a 30% increase over consumption in 1986/87. Almost 50% of the growth between 1986/87 and 1997/98 is expected to occur in the developing nations (World Bank, 1988).

IMPACT OF CLIMATIC CHANGE ON ANTHROPOGENIC EMISSIONS

Climate change will affect human activity in a myriad of ways, and thus influence anthropogenic emissions of greenhouse gases (see Chapter III for a discussion of the biogeochemical feedbacks of climate change). The impact of climatic change on land-use patterns and agricultural practices could be particularly significant in influencing the trace gas emissions from these sources. The magnitude (or even the direction) of such changes have not been examined to date. More information is available regarding the impact of climatic change on electric utilities (Linder et al., 1987). A brief

FIGURE 4-17

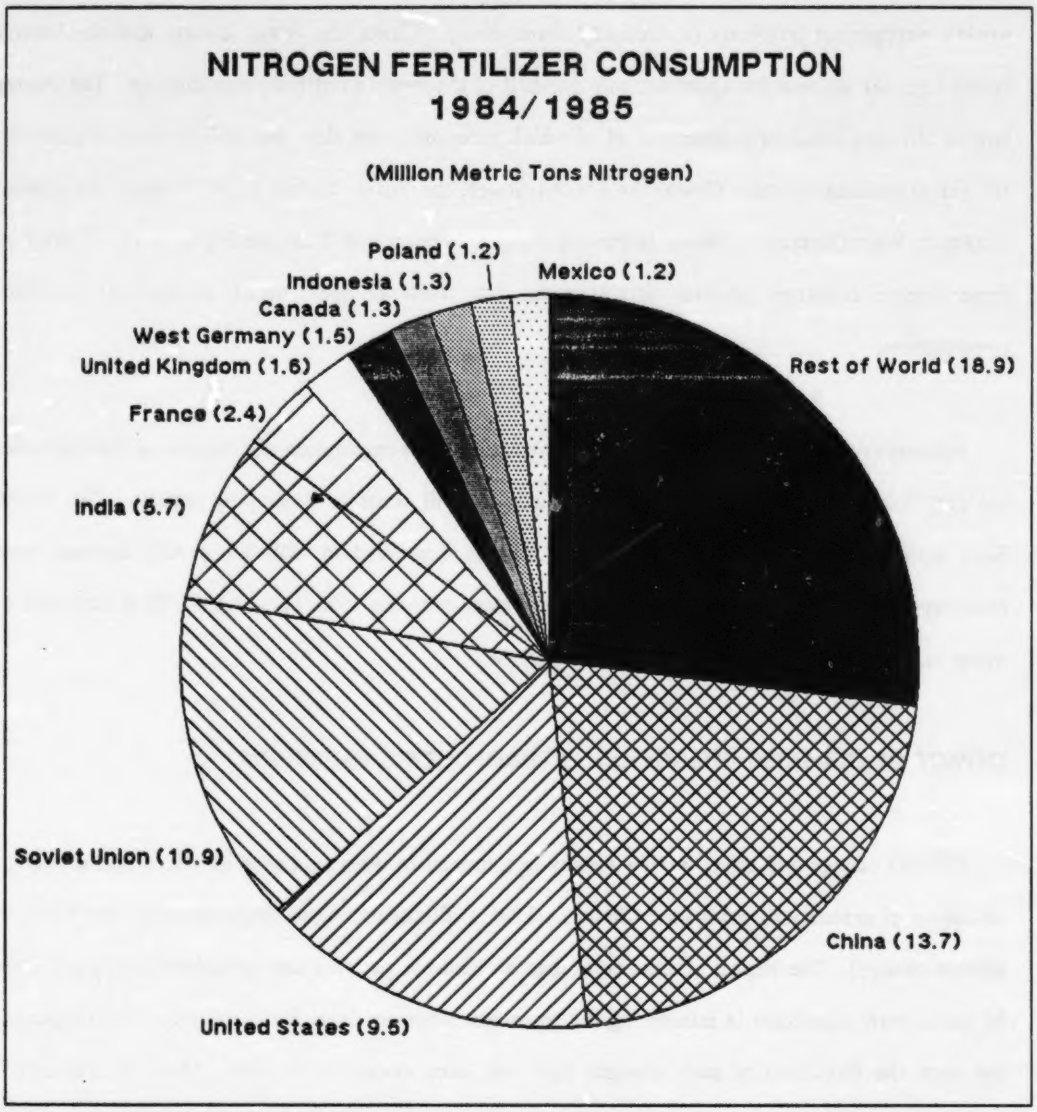

Figure 4-17. Distribution of the total nitrogenous fertilizer consumption of 70.5 million tons N. China, the United States, and the Soviet Union together accounted for just over 50% of the 1984/1985 global fertilizer consumption. Currently, 5-35% of the total anthropogenic N_2O emissions are attributed to nitrogenous fertilizer consumption. (Source: FAO, 1987.)

discussion of this subject is presented here as an illustration of some ways in which climatic change can, in turn, influence trace gas emissions.

Linder and Inglis (1988) estimate that annual electricity consumption increases by 0.5 to 2.7%/°C for utilities in the United States, depending on the local climate and the fraction of buildings with electrical heating and air-conditioning equipment. If climate change leads to increases in ownership levels, then substantially greater sensitivities are possible (Linder et al., 1987). Currently, 37% of total CO_2 emissions from fossil fuels are produced by electric utilities and this share is expected to increase in the future (see Chapter V). Applying the U.S. average sensitivity of 1.0%/°C obtained by Linder and Inglis (1988) to the rest of the world implies a feedback on CO_2 emissions of 0.4%/°C. This feedback would be offset to an extent that has not been estimated by lower fuel use for heating, but as the penetration of air conditioning rises in developing countries this feedback could increase.

Climate change may affect the electricity industry from the supply side as well. When steam is produced to generate electricity in a power plant, either water (usually from a nearby reservoir or river) or air is used as a coolant to condense the steam back into water and start the process over again. Higher atmospheric temperatures will result in warming of these coolants, and reduction in the efficiency of the power plants. This effect is not likely to be as significant as others, however, since seasonal temperature changes are already much greater than the warming predicted for the next century (Linder et al., 1987).

More immediate and acute effects of climate change on electric utilities are likely to occur due to reduced availability of water. The drought of the summer of 1988 resulted in such low river levels in the U.S. Midwest, that some electric plants were forced to reduce generation due to lack of cooling water. More frequent and severe droughts would also result in reduced hydropower for generation of electricity. (This change would also affect barge shipping, since many rivers would become unnavigable, and result in increased trace gas emissions from truck and rail transport.)

Sea-level rise and lowered stream flows resulting from climate change would also have adverse effects on electric utilities. Salinities in rivers and estuaries would increase, and stream chemistry could change, so that the water may become too corrosive to be used as a coolant. A few power plants in the United States use saltwater for cooling purposes, so the technology exists to adapt to more saline coolants, although the conversion process is costly.

These feedback mechanisms are likely to have a smaller influence on future warming than the biogeochemical feedbacks discussed in Chapter III. The impact of climatic change on anthropogenic trace gas emissions may nevertheless prove to be important and should be investigated further.

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CHAPTER V

THINKING ABOUT THE FUTURE

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FINDINGS

- Decisions made in the next few decades, about how electricity is produced, homes are constructed, and cities are laid out, for example, will have an impact on the climate in 2100 and beyond. While it is not possible to predict the level of greenhouse gas emissions over this time period, it is possible to construct scenarios of economic and technological development, and a reasonable range for resulting greenhouse gas emissions, atmospheric concentrations, and global temperature changes. Global temperature change estimates provide an indicator for the rate and magnitude of climatic change.

- Carbon dioxide emissions are likely to grow by a factor of 2 to 5 during the next century if stabilizing policies are not adopted, primarily due to expansion of global coal consumption. Options are available, however, that could stabilize or reduce carbon dioxide emissions. Despite the Montreal Protocol to control CFCs, global emissions of these compounds could remain constant or even increase significantly unless the agreement is strengthened. Methane emissions could increase by 60-100% during the next century unless measures to control these emissions are taken.

- Although per capita emissions of greenhouse gases are currently very low in developing countries, their share of global emissions will rise significantly in the future.

- The relative contribution of carbon dioxide to greenhouse warming is likely to increase significantly in the future. Carbon dioxide accounts for more than 70% of the increased commitment to global warming between 2000 and 2100 in all of the scenarios analyzed in this report. This represents a significantly higher estimate of the role of CO_2 compared to its roughly 50% contribution to global warming in the last few decades, but is similar to the estimated contribution of CO_2 to increases in the greenhouse effect over the last century.

- If there is no policy response to the risk of climatic change carbon dioxide concentrations are likely to reach twice preindustrial levels sometime in the latter half of the 21st Century, but total greenhouse gas concentrations equivalent to this level may occur by 2030 or even earlier, and are likely to occur before 2050.

- Even with modest economic growth and optimistic assumptions regarding technical progress, the world could be committed to an equilibrium warming of 1-2°C by 2000, 2-4°C by 2050 and 3-6°C by 2100 (assuming the climate sensitivity to doubling CO_2 is 2.0-4.0°C). Realized warming would be about 2°C by 2050 and 3-4°C by 2100.

- With rapid, but not unprecedented rates of economic growth, the world could be committed to an equilibrium warming of 1-2°C by 2000, 3-5°C by 2050 and 5-10°C by 2100 (assuming that the climate sensitivity to doubling CO_2 is 2.0-4.0°C). Realized warming would be 2-3°C by 2050 and 4-6°C by 2100. Estimated warming commitments greater than 5°C may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

- The adoption of policies to limit emissions on a global basis, such as simultaneous pursuit of energy efficiency, non-fossil energy sources, reforestation, the elimination of CFCs, and other measures, could reduce the rate of warming during the 21st century by 60% or more. Even under these assumptions, the Earth could ultimately warm by 1-3°C or more relative to preindustrial times. Extremely aggressive policies to reduce emissions would be necessary to ensure that total warming is less than 2°C.

INTRODUCTION

Although technological advances in industry and agriculture have provided extraordinary wealth to a portion of the global population of over 5 billion people, these technologies have the potential to dramatically alter the Earth's climate by causing changes in the composition of the atmosphere as discussed in Chapters II through IV. Global increases in the atmospheric concentrations of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and chlorofluorocarbons (CFCs) are now well documented (Chapter II), perhaps already committing the Earth to significant climatic change. Myriad human activities are contributing to this situation, and continued population and economic growth raises the prospect of accelerated greenhouse gas buildup in the future (Chapter IV).

If current trends in trace-gas concentrations continue, climatic change could be noticeable to the "man-in-the-street" during the 1990s, and the average surface temperature of the Earth could be warmer than at any time in recorded human history by the second decade of the 21st century (Hansen et al., 1988). If the composition of the atmosphere were stabilized by 2000, on the other hand, detectable climatic change is still possible, but its magnitude would be limited and the rate of change might be similar to natural fluctuations recorded in the geologic record (Hansen et al., 1988).

What will happen in the future cannot be predicted. The future evolution of the atmosphere will depend largely on the paths of economic development and technological change, as well as on the physical, chemical, and biological processes of the Earth-atmosphere system. While we have no control over this system once gases enter the atmosphere, economic and technological change will be influenced by policy choices made at local, national, and international levels. This chapter explores some of the paths the world might follow in the decades ahead and provides an indication of the relative climatic consequences under these alternatives. After a discussion of the economic and social factors that determine emissions, four scenarios of economic and technological development are presented. These scenarios cannot capture all the possibilities, of course; rather, they have been developed in order to explore the probable climatic effects under significantly different, but plausible, economic and technological conditions. The climatic implications of these scenarios are analyzed using an integrated framework described briefly in this chapter and in greater detail in Appendix A. The chapter concludes with the results of this analysis and a comparison of these results with other studies.

APPROACH TO ANALYZING FUTURE EMISSIONS

The scope of this analysis must be global, and because of the long lags built into both the economic and climatic systems, this study must consider a time horizon of more than a century--we chose 2100 as the ending year for the analysis. While this is an eternity for most economists and planners, it is but a moment for geologists. And indeed, decisions made in the next few decades, about how electricity is produced, homes are constructed, and cities are laid out, for example, will have an impact on the climate in 2100 and beyond. Decisions about what kinds of automobiles and other industrial products to produce and how to produce them will also have a profound impact. These choices, which will affect the amount and type of fuel we use to travel, to heat and light our homes and offices, and to run our factories, will influence the magnitude of greenhouse gas emissions for many years.

The vast difference between the energy demand projections of the early 1970s and what has actually occurred illustrates the danger inherent in simple trend extrapolations and, indeed, even in making predictions based on results obtained from more complex models. Our approach then is not to attempt to predict the future, but to construct what we believe are logically coherent scenarios of possible paths of economic and technological development. An analytical framework is used to keep track of the assumptions, data, and relationships needed to define the scenarios. Our intent is to define the probable climatic effects under the various economic/social/technological alternatives and, in so doing, increase the likelihood that these consequences will be taken into account when policy decisions are made. If we believe that under a wide variety of assumptions about long-term economic growth and technological change the world will face severe climate problems in the absence of political or economic forces arising from concerns over the greenhouse problem, then it will be necessary to seriously examine the options available for reducing greenhouse gas emissions.

The difficulty we face is that projections of greenhouse gas emissions are very uncertain, because of uncertainties in world economic growth, future fuel prices (which demonstrably affect both the intensities of their use and the substitution amongst alternative energy sources), future rates of land clearing, and rates of technological change, among other factors. For example, both the vagaries of the world oil market in the medium term, as well as true uncertainties regarding the long-term relationship between the cost of producing fossil fuels and the cost of using those fuels in ways that are relatively benign to the local environment, mean that at best we can only guess at future fossil fuel use.

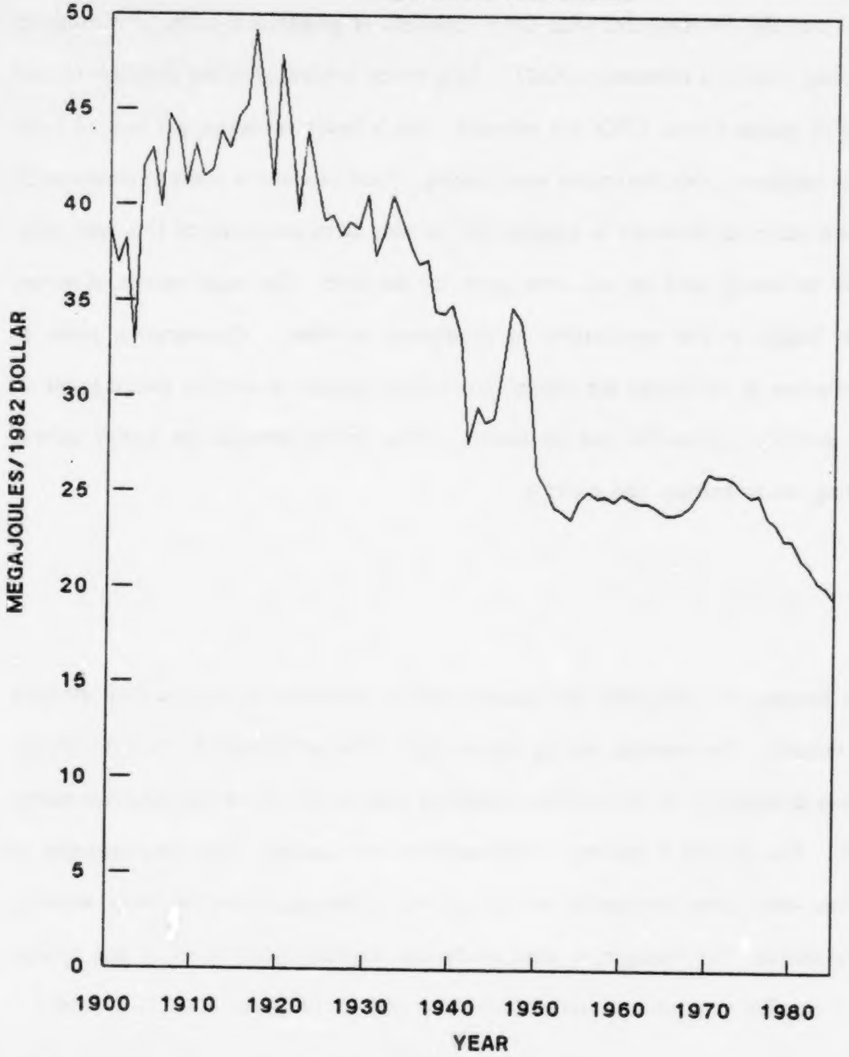
Another avenue of analysis, however, yields information that can guide policy makers faced with these uncertainties. If we can construct scenarios of future energy demand, land-clearing rates, CFC production, etc., that are driven by reasonable assumptions about population, economic growth, technologies, and energy prices, then we can develop a plausible range of future greenhouse gas emissions. To accomplish this task we must consider the structural factors that determine the quantities and patterns of emissions of radiatively-important gases (i.e., those gases whose presence in the atmosphere contribute to a greenhouse warming).

It is conceptually useful to distinguish between production activities and consumption activities. Production emissions arise largely from the processing of bulk materials--steel from ore, plastics from petroleum, cement and glass from limestone and silicate rock--which requires large amounts of energy per unit of industrial value added (i.e., the difference in value between an industry's products and its inputs) and may also be associated with direct emissions of greenhouse gases. For example, during cement making, $CaCO_3$ is reformed to $CaO + CO_2$, which is released to the atmosphere, and during the making of plastic foams, CFCs are released. Much lower emissions per unit of value added are generally associated with fabrication and finishing. Food production leads to emissions of methane and nitrous oxide as discussed in Chapter IV, as well as to emissions of CO_2 and other gases as a result of the energy used on and, even more, off the farm. The large amount of energy required to move freight is also attributable to production activities. Consumption leads to greenhouse gas emissions as individuals use energy, primarily in pursuit of comfort (heating and air conditioning) and mobility (automobile and air travel). Other major end-uses for energy include refrigeration, lighting, water heating, and cooking.

Production

As societies develop over time, both the quantity and the structure of activities that influence emissions change radically. For example, energy use per unit of Gross National Product (GNP) has declined steadily and dramatically in industrialized countries, even in periods of declining real energy prices (Figure 5-1). This decline is due to a combination of two factors. First, improvements in production processes, which often save capital and labor as well as energy, reduce the energy intensity per ton of physical output. For example, in steel production modern energy recovery and process technology make it possible to produce a ton of steel using only $13x10^9$ joules (13 GJ) of final

FIGURE 5-1



TOTAL U.S. ENERGY CONSUMPTION PER GNP DOLLAR
1900-1985
(Megajoules/1982 Dollar)

Sources: U.S. DOE, 1987a; U.S. Bureau of the Census, 1975.

energy, less than half of the current U.S. average.[1] New processes under development in Sweden (Elred and Plasma-Smelt) that integrate a number of operations have even lower energy requirements and reduced overall costs (Goldemberg et al., 1988). Second, the bulk of value added by industry tends to shift from basic materials processing to fabrication and finishing as a country's infrastructure matures. Strout (1985) suggests that consumption of steel, cement, and other raw materials begins to decline after income surpasses about $5000 (1985$) per capita (Figure 5-2). These shifts in technology and the mix of products generally increase the share of energy consumed as electricity, but do not significantly increase absolute electricity intensity because efficiency in electric end-uses improves as well (Kahane, 1986). Rapid economic growth over the long term can be expected to accelerate the reduction of industrial energy intensity in wealthier countries by promoting the replacement of old plant and equipment with more efficient technology, as well as by accelerating the shift toward a less energy-intensive product mix.

In industrialized societies services such as public and private administration, health care, and education, are likely to grow faster than GNP, both because much of industry is being redefined as services and because much of our new wealth is being created by the development and transfer of information. Heating, air conditioning, and lighting, which dominate energy and electricity use in buildings today, will become less energy-intensive (even as indoor environmental quality continues to rise) as more efficient technology is adopted. At the same time, information technology is exerting upward pressure on electricity use per square foot in office buildings and schools. The Business Services sector depends more on electricity than does any other sector in the economy, although it still uses less electricity per unit of output than industry. If there is a large increase in electricity use in industrialized countries, it will come from a massive expansion of the service sector.

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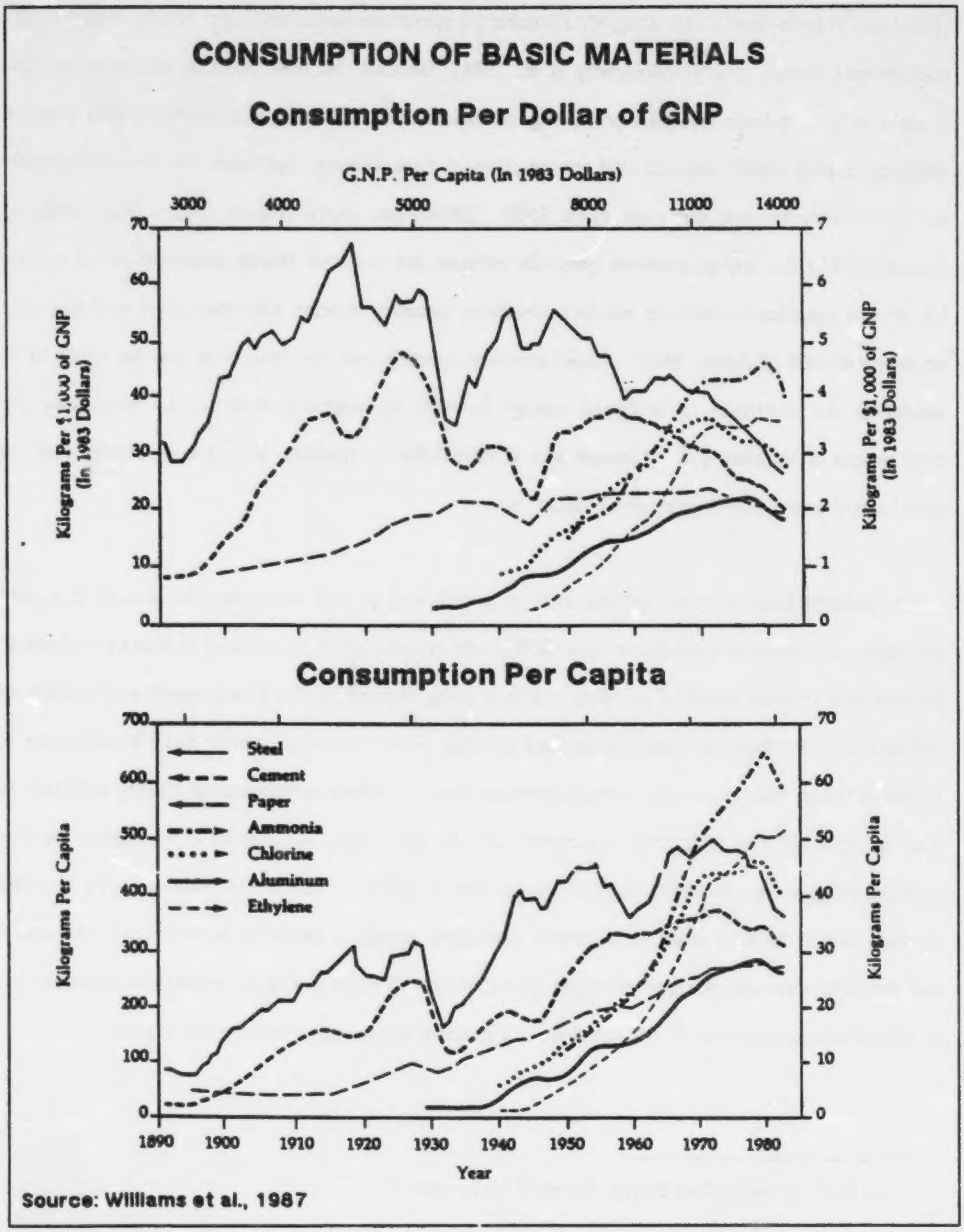
[1] 1 GJ = 0.948 million British Thermal Units (BTU).

FIGURE 5-2



CONSUMPTION OF BASIC MATERIALS

Consumption Per Dollar of GNP

Consumption Per Capita

Source: Williams et al., 1987

The greatest potential for large increases in production-related emissions lies in developing countries. As these countries expand their industrial infrastructure the demand for basic materials could skyrocket. But developing countries have the opportunity to take advantage of new processes and materials that sharply reduce the energy required to produce a given level of amenity. As a result, it is unlikely that materials and energy intensity per capita in developing countries would reach the levels of industrialized countries today, even as similar levels of per capita income are achieved. The extent to which developing countries seize these kinds of opportunities will strongly influence future greenhouse gas emissions.

Consumption

The factors influencing emissions arising from consumption are quite different from those that affect production. In developing countries energy use in consumer products can be expected to increase rapidly as the number of households that can afford to acquire fans, televisions, refrigerators, and automobiles grows. Part of the reason that developing country energy demand has historically increased faster than it did in OECD countries is that developing-country households can afford to purchase these products at lower income levels than was the case for industrialized-country households. The declining price-to-income ratios for many of the energy-intensive consumer goods make this possible, with the consequence that developing country energy consumption tends to grow more rapidly than the experience of the industrialized countries might indicate. At the same time, the efficiency of many of these products is increasing, so that per capita energy consumption in developing countries may not reach the levels of industrialized countries today, even if these income levels are surpassed.

As a society becomes wealthier, the penetration of energy-intensive equipment saturates (there are, for example, 600 cars for every 1000 people in the U.S. compared to 6 in Asian countries), and changes in the efficiency of the stock and how the stock is used becomes more important than changes in the levels of ownership alone. For example, as automobile ownership shifts from corporate to private hands the number of vehicles increases dramatically, but the miles driven per vehicle declines. Consumers rarely consider energy use in making major purchases, and many key decisions that determine energy requirements are made by developers rather than the consumers who pay the energy bills (Ruderman et al., 1987). Increased amenity levels can often be achieved while simultaneously reducing energy use and emissions (better insulated houses are more comfortable because they are less drafty and more efficient air conditioners are usually quieter), but more affluent consumers are likely to choose powerful cars and spacious dwellings, paying less attention to the associated operating costs. Further, because a very wide range of efficiency can be achieved with a small impact on total costs over the life-cycle of the product (see Chapter VIII; von Hipple and Levi, 1983; Ruderman et al., 1987), consumers who are concerned about initial cost are unlikely to choose a product whose level of efficiency is optimal from a social perspective.

The level and pattern of mobility may be the most significant uncertainty in future energy use. Will we spend our free time in our air-conditioned homes watching rented movies on the VCR/TV, or are we more likely to drive to the countryside to go for a hike? Not surprisingly, the pattern of automobile use at present (roughly 1/3 of all passenger-kilometers driven in the U.S. are to/from work, 1/3 are for family business, and 1/3 are in pursuit of leisure activities; OTA, 1988) is a function both of distances among where we live, work, and relax, and of how often we choose to move about. Similarly, airline travel, already dominated in the U.S. by personal rather than business travel, is more and more determined by how and where people want to spend their free time. Meanwhile in cities like Hong Kong and Sao Paulo, but also in New York and Los Angeles, congestion is increasingly constraining automobile use. The level of fuel economy and emissions achieved by a particular automobile in practice is very sensitive to average speed, which is down to about 15-20 miles per hour in L.A. and under 10 miles per hour in New York City (Walsh, personal communication). How and whether cities solve these congestion problems--with roads, car pools, buses, light rail, or all of the above--will have a large impact on both urban and global environmental quality.

SCENARIOS FOR POLICY ANALYSIS

In order to explore some of the implications of the relationships discussed briefly above, we have constructed four scenarios of future patterns of economic and technological development starting with alternative assumptions about the rate of economic growth and the adoption of policies that influence climatic change (Table 5-1). These four scenarios cannot capture all the possibilities of course; rather, they allow us to explore likely climatic outcomes and the impact of strategies for stabilizing the atmosphere. The sensitivity of the results to a wide range of specific assumptions has been tested and is discussed in Chapter VI.

Two scenarios explore alternative pictures of how the world may evolve in the future assuming that policy choices allow unimpeded growth in emissions of greenhouse gases (these are referred to as the "No Response" scenarios). One of these scenarios, called a Rapidly Changing World (RCW), assumes rapid economic growth and technical change; the other assumes more gradual change and is called the Slowly Changing World (SCW). That is, we have invented a future with relatively high and robust economic growth, and one representing a more pessimistic view of the evolution of the world's economies. The first world would likely illustrate the upper half of the potential range of future greenhouse gas emissions, because in general higher economic activity means a higher total

TABLE 5-1

Overview of Scenario Assumptions

Slowly Changing World	**Rapidly Changing World**
Slow GNP Growth	Rapid GNP Growth
Continued Rapid Population Growth	Moderated Poulation Growth
Minimal Energy Price Increases	Modest Energy Price Increases
Slow Technological Change	Rapid Technological Improvements
Carbon-Intensive Fuel Mix	Very Carbon-Intensive Fuel Mix
Increasing Deforestation	Moderate Deforestation
Montreal Protocol/Low Participation	Montreal Protocol/High Participation

Slowly Changing World with Stabilizing Policies	**Rapidly Changing World with Stabilizing Policies**
Slow GNP Growth	Rapid GNP Growth
Continued Rapid Population Growth	Moderated Population Growth
Minimal Energy Price Increases/Taxes	Modest Energy Price Increases/Taxes
Rapid Efficiency Improvements	Very Rapid Efficiency Improvements
Moderate Solar/Biomass Penetration	Rapid Solar/Biomass Penetration
Rapid Reforestation	Rapid Reforestation
CFC Phase-Out	CFC Phase-Out

energy use and emissions; conversely, the second world could serve as a useful guide to the lower half of the range. In either case, our scenarios are first constructed as if there were no interventions motivated by global climate problems.

In constructing these two worlds/scenarios, we have borne two important ideas in mind. First, evidence is clear that with more rapid economic growth, energy efficiency improves more rapidly than with slower growth (Schurr, 1983). This occurs because innovation proceeds more rapidly and because older, less efficient systems are more rapidly replaced with new technology. History shows, for example, that for almost every country, energy efficiency in industry increases with increasing incomes, as sophistication and scale win over brute force. At the same time, higher incomes allow people to spend more money on two key energy-intensive uses, space conditioning (heating and air conditioning), and automobiles. Thus not all of the technological benefits of rapid economic growth put the brakes on overall energy use. But more rapid economic growth does allow society to put resources aside to improve the efficiency of both space comfort and personal transportation. Similar patterns can be expected in other emissions sectors.

Conversely, slower economic growth retards innovation, in part because both consumers and producers do not see bright economic times that make innovation and expansion into new technologies useful. Comfort and mobility still manage to increase as important drivers of personal energy demand, but at a slower rate. When these two paths are compared, the effect of more rapid efficiency increases in the higher growth world is to narrow the difference in greenhouse gas emissions; that is, the likely difference between emissions in the Rapidly and Slowly Changing Worlds is less than the differences in Gross National Product. This result makes our scenarios somewhat more robust than one might otherwise think.

The second idea concerns energy prices. In a world of high and robust economic growth, which we have assumed in the Rapidly Changing scenario, energy demand will likely increase, and in the medium term, so will energy prices. Yet if energy efficiency increases, then energy costs can increase more rapidly than the rate of economic growth and still not consume an increasing share of national wealth and income. In other words, energy prices can rise without putting the brakes on economic growth, as long as the price increases are gradual (CONAES, 1979). But in a world of sluggish economic growth, energy demand rises more slowly, so that energy prices would rise very little. This idea is an additional reason why we believe that energy efficiency increases more rapidly in the high growth scenario (RCW) than in the low growth scenario (SCW).

With these ideas in mind, we can build scenarios of world energy demand by end use and region as well as levels of other activities that emit greenhouse gases. The scenarios are not exact predictions, but serve as guides to the level of emissions associated with each important purpose or end use in the worlds we constructed.

One benefit of using this approach is that we can compare the utilization efficiencies that we assume for the No Response scenarios with those we believe achievable if more than just market forces were acting. Two additional scenarios (referred to as the "Stabilizing Policy" scenarios) start with the same economic and demographic assumptions, but examine the effect that policies could have on global warming. These scenarios are called the Slowly Changing World with Stabilizing Policies (SCWP) and the Rapidly Changing World with Stabilizing Policies (RCWP).

Using our best information about technologies that could become available, or technologies that are already available but not taken up by the market because of market failures or other reasons, we can reconstruct activity patterns that are still consistent with our overriding economic assumptions, but produce much lower levels of greenhouse gas emissions. Key changes are assumed in energy efficiency, the energy supply mix, land-clearing rates, and other factors that might be changed by government policies or other means.

In other words, we keep the basic scenarios but, for example, manipulate important energy use patterns within these scenarios. These manipulations can only be carried out if greenhouse gas emissions in each scenario are constructed from the bottom up, i.e., by specifying the level of each major-emitting activity, as well as the emissions per unit of activity (e.g., total harvested rice paddy area and methane emissions per square meter of paddy).

Thus the scenarios we constructed are a necessary step towards illustrating both ranges of greenhouse gas emissions under two quite different assumptions about economic growth, and where there is scope for reducing emissions through a variety of strategies. In the final analysis, our work can be turned around: we can consider the levels of emissions that under the best and worst assumptions about how emissions are coupled to climatic change leave the world's climate tolerable.

Scenarios with Unimpeded Emissions Growth

In a "Slowly Changing World" (SCW) we consider the possibility that the recent experience of modest economic growth will continue indefinitely, with no concerted policy response to the risk of climatic change. In this scenario we assume that the aggregate level of economic activity (as measured by GNP) increases relatively slowly on a global basis (Table 5-2). Per capita income is stagnant for some time in Africa and the Middle East as rapid population growth continues. Modest increases in per capita income occur elsewhere, and per capita growth rates increase slightly over time in all developing countries as population growth rates slowly decline (Figure 5-3). The share

TABLE 5-2

Economic Growth Assumptions

(percent per year)

			Slowly Changing World		Rapidly Changing World	
	1965-1975	1975-1985	1985-2025	2025-2100	1985-2025	2025-2100
US & OECD	3.9	2.8	1.7	1.0	2.7	1.5
USSR & Eastern Europe	6.2	NA	2.2	1.6	4.3	2.6
Centrally Planned Asia	7.0	7.8	3.2	2.5	5.1	4.0
Other Developing Countries	5.6	3.2	2.7	2.1	4.5	3.3
World	4.4	2.9[a]	2.0	1.5	3.4	2.6

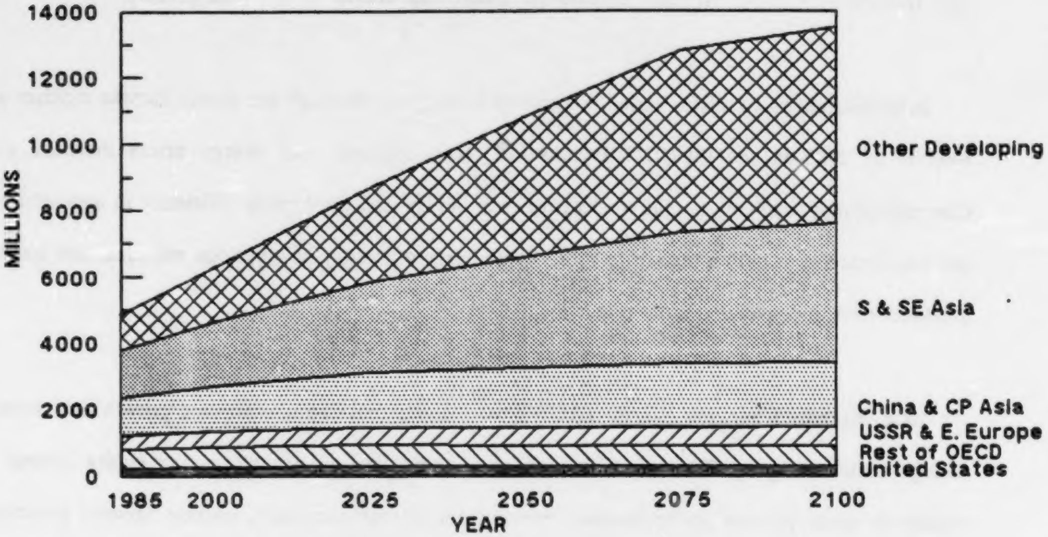
[a] Excludes USSR and Eastern Europe.

Source: IMF, 1988.

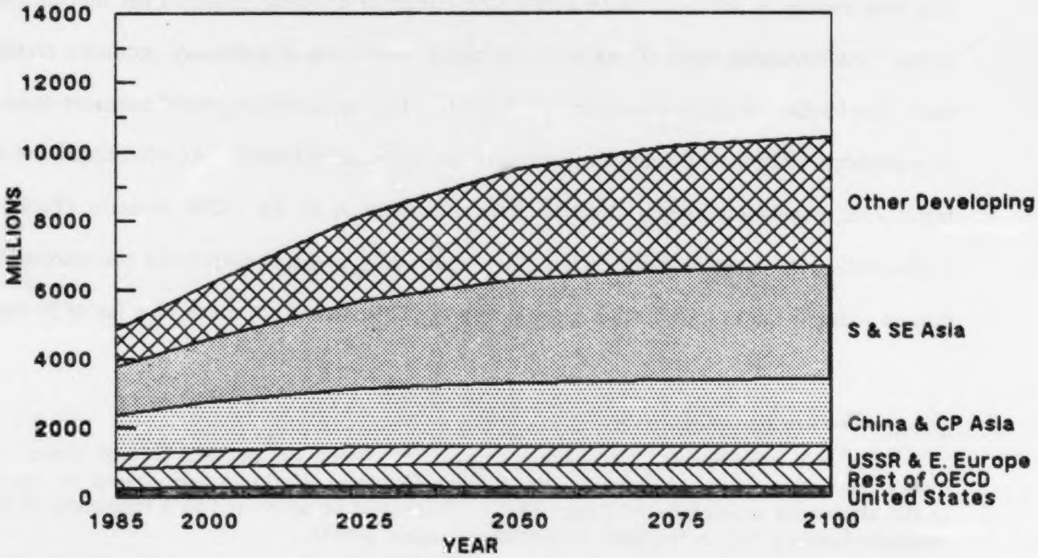
FIGURE 5-3

POPULATION BY REGION
(Millions)

Slowly Changing World



Rapidly Changing World



Source: U.S. Bureau of the Census, 1987

of global income going to the developing world does increase with time, but not dramatically. The population engaged in traditional agriculture and shifting cultivation continues to increase, as do demand for fuelwood and speculative land clearing. These factors lead to accelerated deforestation until tropical forests are virtually eliminated toward the middle of the next century.

In industrialized countries economic growth is sluggish, although per capita income reaches about $40,000 by 2100 in the OECD. Because of slack demand, real energy prices increase slowly. Correspondingly, existing capital stocks turn over slowly and production efficiency in agriculture and industry improve at only a moderate rate. The energy efficiency of buildings, vehicles, and consumer products also improve at a slow rate.

In a "Rapidly Changing World" (RCW) we assume that rapid economic growth and structural change occurs and that little attention is given to the global environment. Per capita income rises rapidly in most regions and consumer demand for energy increases, putting upward pressure on energy prices. On the other hand, there is a high rate of innovation in industry, and capital stocks turn over rapidly, which leads to an accelerated reduction in energy required per unit of industrial output. An increasing share of energy is consumed in the form of electricity, produced mostly from coal. The fraction of global economic output produced in the developing world increases dramatically as post-industrial structural change continues in the industrialized world. As educational and income levels rise, population growth declines more rapidly than in the SCW scenario (Figure 5-3).[2] Deforestation continues at about current rates, spurred by land speculation and commercial logging, despite reduced rates of population growth. Energy efficiency is not much of a factor in consumer decisions, as incomes increase faster than real energy prices. Private vehicle ownership increases rapidly in developing countries while air travel increases rapidly in wealthier ones. Nonetheless, significant reductions in energy intensity occur with technological innovation and structural change.

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[2] The sole exception is China, where aggressive policies are assumed in both cases. Slightly higher population growth is shown in the Rapidly Changing World scenario based on the sources of the alternative estimates (see Appendix B). This could be attributed to a relaxation of the one-child-per-family policy in response to greater economic growth.

Scenarios with Stabilizing Policies

Two variants of the above scenarios explore the impact of policy choices aimed at reducing the risk of global warming. These scenarios, labelled "Slowly Changing World with Stabilizing Policies" (SCWP) and "Rapidly Changing World with Stabilizing Policies" (RCWP), start with the same economic and demographic assumptions used in the SCW and RCW scenarios, respectively, but assume that government leadership is provided to ensure that limiting greenhouse gas emissions becomes a consideration in investment decisions beginning in the 1990s. We assume that policies to promote energy efficiency in all sectors succeed in substantially reducing energy demand relative to the No Response scenarios and that efforts to expand the use of natural gas increase its share of primary energy supply relative to other fossil fuels in the near term. Research and development into non-fossil energy supply options such as photovoltaics (solar cells) and biomass-derived fuels (fuels made from plant material) assure that these options are available and begin to become competitive after 2000. As a result, non-fossil energy sources meet a substantial fraction of total demand in later periods. The existing protocol to reduce CFC emissions is assumed to be strengthened, leading to a phase-out of fully-halogenated compounds and a freeze on methyl chloroform. A global effort to reverse deforestation transforms the biosphere from a source to a sink for carbon, and technological innovation and controls reduce agricultural, industrial, and transportation emissions.

While these general assumptions apply to both the SCWP and RCWP cases, the degree and speed of improvement are higher in the Rapidly Changing variant because technological innovation and capital stock replacement are greater in this case. The policies considered do not require changes in basic life styles. For example, energy use in buildings is greatly reduced in the Stabilizing Policy scenarios relative to the No Response scenarios, but the floor space available per person and the amenity levels provided are assumed to be the same. The technological strategies and policy options available to achieve the Stabilizing Policy scenarios are discussed in detail in Chapters VII, VIII, and IX.

ANALYTICAL FRAMEWORK

To make it possible to assess the implications of the kinds of scenarios just described, we have developed an integrated analytical framework to organize the data and assumptions required to calculate emissions of radiatively and chemically active gases, concentrations of greenhouse gases, and the rate of climatic change. This framework is described very briefly here, and in more detail in Appendix A.

The analytical framework consists of four emissions modules and two concentration modules as shown in Figure 5-4. The four emissions modules use input data, including scenario specifications for population growth, GNP, energy efficiency, etc., to estimate emissions of greenhouse gases for nine regions of the globe (Figure 5-5). Emissions are calculated every 5 years from 1985 to 2025 and then every 25 years through 2100. Emissions of the greenhouse gases CO_2, CH_4, N_2O, and a number of CFCs are explicitly calculated within the framework. Emissions of CO and NO_x, which are not themselves greenhouse gases, are also explicitly calculated, as these gases can significantly alter the chemistry of the atmosphere and thus affect the concentrations of the greenhouse gases.

FIGURE 5-4

Structure of the Atmospheric Stabilization Framework

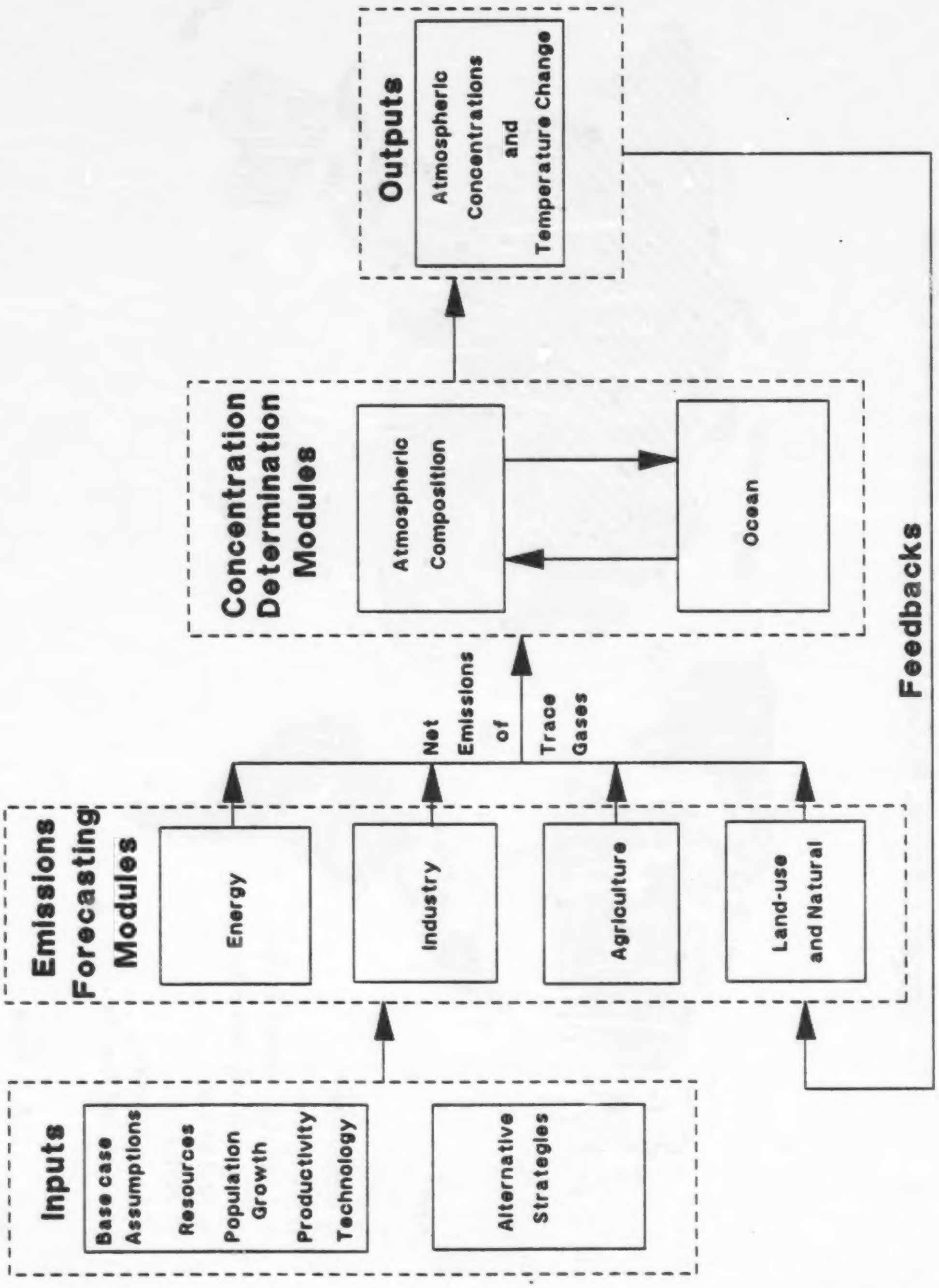
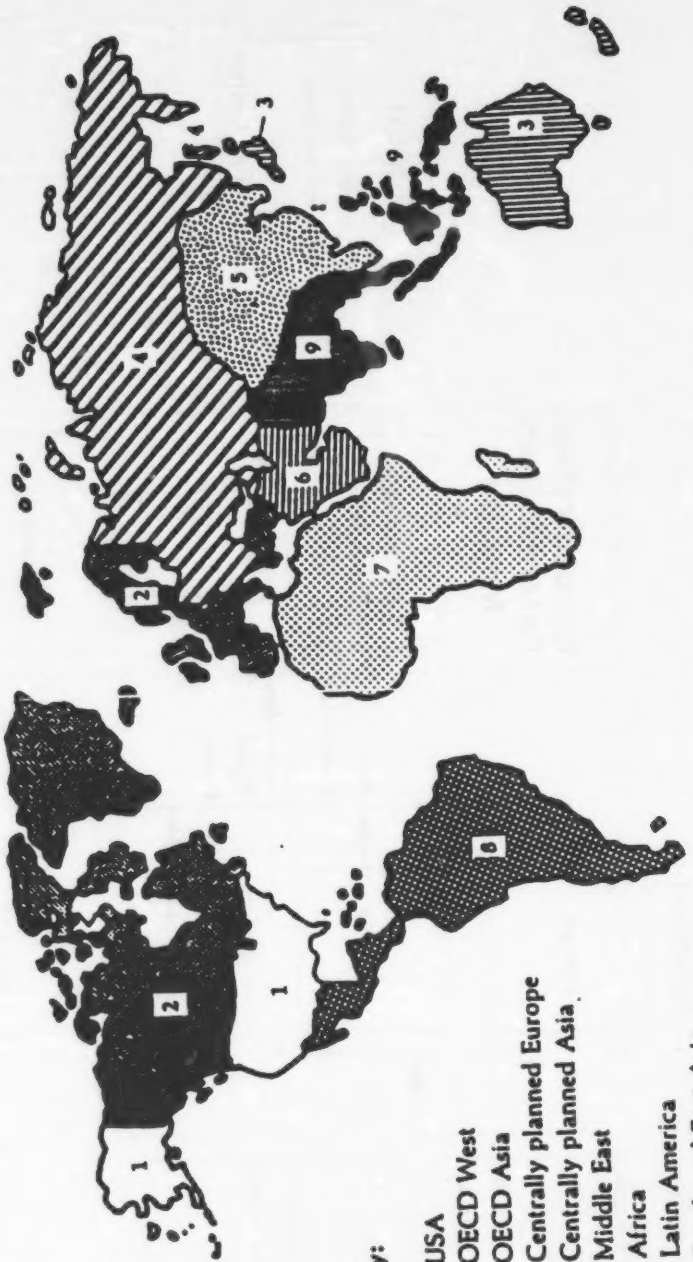

Inputs
Base case Assumptions
Resources
Population Growth
Productivity
Technology
Alternative Strategies
Emissions Forecasting Modules
Energy
Industry
Agriculture
Land-use and Natural
Net Emissions of Trace Gases
Concentration Determination Modules
Atmospheric Composition
Ocean
Outputs
Atmospheric Concentrations and Temperature Change
Feedbacks

FIGURE 5-5

GEOPOLITICAL REGIONS FOR CLIMATE ANALYSES



Key:

1. USA
2. OECD West
3. OECD Asia
4. Centrally planned Europe
5. Centrally planned Asia
6. Middle East
7. Africa
8. Latin America
9. South and East Asia

Source: Mintzer, 1988.

The concentrations of other greenhouse gases, such as water vapor and ozone, are calculated implicitly or explicitly as a function of the other gases. The atmospheric composition and ocean modules together estimate global concentrations of the greenhouse gases resulting from the projected emissions, and increases in global temperatures resulting from the calculated concentrations. The atmospheric trace gas concentrations and temperatures affect the emissions and concentration modules in the next time period.

Energy Module

The energy module consists of a Global Energy Supply Model (SUPPLY), which is based on the energy-CO_2 model of Edmonds and Reilly (1983a, 1984), and was developed by ICF Inc. for this study; a global energy end-use analysis (DEMAND), conducted by the World Resources Institute and Lawrence Berkeley Laboratories; and combustion emission coefficients developed by Radian (1987).

DEMAND estimates energy consumption based on specific assumptions about the level of energy using activities and technical efficiency by region and sector (industry, transportation, buildings). Although this analysis provided more detail than most previous global studies, this level of aggregation obscures many important variations, particularly for developing countries. For example, per capita incomes vary from $150 for Bangladesh to $7000 for Singapore within the South and East Asia region. The share of energy used by the manufacturing sector, vehicle ownership levels, and types of fuels used (particularly the importance of biofuels), all vary from one economy to another. In conducting the analysis we capture some of this diversity by examining energy use by regions and by income groups within regions. Detailed analysis was performed for 2025 to anchor the demand estimates calculated for other years using SUPPLY.

SUPPLY includes estimates of energy resources and costs by region and can balance supply and demand using a highly-aggregated estimate of demand as a function of price and income. Supply-demand equilibration takes place within SUPPLY, which projects fuel mix and final prices. Trace-gas emissions are calculated by allocating the final fuel consumption among the individual combustion technologies for which emission coefficients are available. Additional emissions associated with fuel production are also estimated.

Industry Module

The industry module consists of a CFC model and a model for other non-combustion trace-gas sources. The CFC model was developed by EPA for use in assessing stratospheric ozone depletion (U.S. EPA, 1987). It projects production and emissions of the following compounds: CFC-11, CFC-12, HCFC-22, CFC-113, CCl_4, CH_3CCl_3, CH_3C1, CH_3Br, CF_4, Halon 1211, and Halon 1301. Other industrial sources of trace gases include landfilling and cement production. Emissions from these activities are estimated as a simple function of population and per capita income.

Agriculture Module

The agricultural module uses the IIASA/IOWA Basic Linked System, or BLS, (Frohberg, 1988) to forecast fertilizer use and agricultural production. These estimates are used with emission coefficients derived from the literature to calculate emissions of N_2O from fertilizer use, CH_4 from rice production, CH_4 from enteric fermentation in domestic animals, and emissions of CH_4, N_2O, NO_x, and CO from burning agricultural wastes.

Land Use and Natural Source Module

This module consists of components dealing with a number of land surface processes and other natural sources of trace gases. The most important of these is carbon dioxide released from land use change, particularly deforestation, which is projected with the Marine Biological Laboratory/Terrestrial Carbon Model, or MBL/TCM, (Houghton et al., 1983) based on assumptions about future rates of land clearing. Other anthropogenic emissions related to land clearing, such as a portion of CO emissions from biomass burning and N_2O emissions from land disturbance, are scaled based on the CO_2 emissions calculated by the MBL/TCM. Natural emissions of CO, CH_4, N_2O, and NO_x from sources such as forest fires, wetlands, soils, oceans, and fresh water are based on values from the literature, and generally are held constant throughout the projection period (biogeochemical feedbacks can be assumed to alter these emissions, see Chapter VI).

Ocean Module

Ocean uptake of heat and CO_2 are modeled using the Box-Diffusion approach introduced by Oeschger et al. (1975) as implemented for the GISS GCM (Hansen et al., 1984). The ocean mixing parameter for heat uptake is chosen to reproduce, as closely as possible, the timescales obtained in the time-dependent calculations with the GISS GCM (Hansen et al., 1988). Alternative values for this parameter can be used to approximate the timescales of other approaches to estimating ocean heat uptake (Chapter VI). Alternative ocean model formulations for CO_2, such as the Advective-Diffusive Model (Bjorkstrom, 1979) and the Outcrop-Diffusion Model (Siegenthaler, 1983), are included in the integrating framework and can be used for alternative estimates of CO_2 uptake. Total carbon uptake is calibrated using estimates of historical emissions of CO_2 from fossil fuels (Rotty, 1987a,b) and deforestation (Houghton, 1988). The atmospheric CO_2 concentration is assumed to be

285 ppm in 1800 and is forced to be equal to the values obtained at Mauna Loa for the period of record (1960-1985). The excess flux required to meet these conditions is calculated and held constant in the future at the average value for 1975-1985. Alternative assumptions are considered in Chapter VI.

Atmospheric Composition and Temperature Module

The atmospheric composition model was developed for this study (Prather, 1988). It estimates changes in the concentration of key atmospheric constituents and the global radiation balance based on the emissions/uptake projected by the other modules. Perturbations to atmospheric chemistry are incorporated based on first-order (and occasionally second-order) relationships derived from more process-based chemical models and observations. The model is essentially zero-dimensional, but it does distinguish between the northern hemisphere, southern hemisphere, troposphere, and stratosphere. Global surface temperature change is calculated based on the radiative forcing of the greenhouse gases derived from Lacis et al. (1981) and Ramanathan et al. (1985) coupled to heat uptake by the ocean model using a specified climate sensitivity parameter. This sensitivity parameter is set to yield a global equilibrium temperature increase of 2 or 4°C when the CO_2 concentration is doubled, reflecting a central estimate of the range of uncertainty; a broader range of possibilities is examined in Chapter VI (see discussion in Chapter III).

Assumptions

Population Growth Rates

The population estimates for the Rapidly Changing World scenario were developed from Zachariah and Vu (1988) of the World Bank; for the Slowly Changing World scenario estimates were taken from U.S. Bureau of the Census (1987) of the U.S. Bureau of the Census. These two sources agree quite closely on the size of the world's population through 2000, then diverge thereafter due to different assumptions on the rate at which the global population will stabilize. Zachariah and Vu (1988) assumes that population growth rates in developing countries will begin to decline markedly after 2000, achieving a net reproduction rate of unity in every country by 2040. (A net reproduction rate of unity indicates that people of child-bearing age have children at a replacement rate; it eventually leads to a stable population level.) U.S. Bureau of the Census (1987) assume that global population stability will occur at a later date, with developing countries experiencing rapid population growth rates until the middle of the next century.

Economic Growth Rates

The primary source for the economic growth rate estimates was the World Bank (1987). In their report, Gross National Product (GNP) forecasts were provided for the 1986-1995 period for several different types of country groups. Most countries could be classified into one of these three general categories--low income, middle income, or industrialized. In addition, the World Bank defined several other more select groups for which separate growth rates were estimated, including oil exporters, exporters of manufactures, highly-indebted countries, and sub-Saharan Africa. The low growth case was used as a starting point for this analysis because these estimates were more consistent with recent historical trends and other forecasts. For the RCW (SCW) scenario these initial values were generally increased (decreased) by one percentage point for developing and East Bloc countries and one-half percentage point for OECD countries to reflect the greater uncertainty regarding future growth in developing and centrally-planned economies. The growth rates were applied for the period 1985-2000, and were generally reduced by one-half percentage point each 25-year period, beginning in 2000, to reflect structural change and the decline in population growth rates over time. Nonetheless, GNP per capita continues to increase throughout the projection period, although the rate of growth is substantially lower in the Slowly Changing World scenario.

Oil Prices

The oil prices used in this analysis were taken from U.S. DOE (1988), which supplied a range of oil price forecasts. The Middle Price forecast from DOE was used for the Rapidly Changing World scenario (by 2000 the world oil price is about $31/barrel in 1987 dollars), while the Low Price forecast was used for the Slowly Changing World scenario (oil prices by 2000 were about $25/barrel in 1987 dollars). Since the DOE price forecasts did not extend beyond 2000, oil prices were derived from the SUPPLY model; in each scenario prices escalated about 0.8% annually from 2000-2100.

Limitations

This analytical framework attempts to incorporate some representation of the major processes that will influence the rate and magnitude of climatic change during the next century within a structure that is reasonably transparent and easy to manipulate. In so doing we recognize a number of major limitations:

- Economic growth rates are difficult to forecast. Our alternative assumptions may not adequately reflect the plausible range of possibilities. In particular, we have assumed that aggregate economic growth rates will generally decline over time from the levels assumed for 1985-2000; this may not be the case.

- Economic linkages are not fully captured. The economic analysis uses a partial-equilibrium framework, making it impossible to ensure that the activity levels assumed in each sector are completely consistent with the aggregate economic assumptions. In addition, capital markets are not explicitly considered. This is particularly significant in examining developing countries as it is unclear if they will be able to obtain the capital investments needed to develop the energy supplies assumed in some of the scenarios.

- Technological changes are difficult to forecast. Substantial improvements in the efficiency of energy using and producing technologies are assumed to occur even in the absence of substantial energy price increases or policy measures. If this assumption proves to be untrue, then greenhouse gas emissions may be substantially underestimated in the No Response scenarios. Similarly, aggressive research and development is assumed to substantially reduce the cost of renewable technologies in the Stabilizing Policy scenarios. The impact of policies may be overestimated if such improvements fail to materialize or if they would have materialized as rapidly even without increased government support.

- Detailed cost analyses have not been conducted. Technological strategies have been screened based on judgments about their potential cost-effectiveness, but no attempt has been made to rank the cost-effectiveness of each strategy or to estimate the government expenditures or total costs associated with the stabilizing strategies.

- The modules of the framework are not fully integrated. Existing models of individual processes that affect greenhouse gas emissions were assembled within the analytical framework and were used with consistent assumptions. However, it was not possible to ensure complete consistency of results. For example, while the biomass energy supplies arrived at in the Energy module do not appear to be inconsistent with the land use patterns calculated in the Agriculture and Land Use and Natural Source modules, there is no explicit coupling among these results.

- The ocean models employed are highly simplified. The ocean plays an important role in taking up both CO_2 and heat. The one-dimensional models used to represent this process may not adequately reflect the underlying physical processes, particularly as climate changes.

- Changes in atmospheric chemistry are calculated in a highly-simplified fashion. Chemical interactions are analyzed based on parameters derived from detailed chemical models. These parameters may not adequately reflect the underlying chemistry, particularly as the atmospheric composition changes significantly from current conditions. Also, it is not possible to explicitly model the heterogeneous conditions that control, for example, tropospheric ozone concentrations. In our analysis we also assume that non-methane hydrocarbon emissions remain constant, which may cause future methane and ozone changes to be underestimated.

SCENARIO RESULTS

We have estimated the implications of the four scenarios described above for emissions of radiatively-important gases arising from energy production and use, industrial processes, changes in land use, and agricultural activities using the integrated analytical framework developed for this study. The resulting changes in atmospheric composition and global climate are also estimated.

Energy Sector

The single most important determinant of greenhouse gas emissions is the level of energy demand and the combination of sources that are used to supply that energy.

End-use Consumption

Government policies that affect demand for energy are likely to be the most important determinant of greenhouse gas emissions in the near term. Figures 5-6 and 5-7 illustrate global end-use energy consumption by region for fuel and electricity, respectively. Total end-use energy consumption increases from 220×10^{18} joules (220 EJ) in 1985 to 320 EJ in 2025 in the SCW versus 420 EJ in the RCW.[3] Greater improvements in energy efficiency in the SCWP and RCWP cases reduce end-use demand in 2025 by 13% and 15%, respectively, relative to the No Response scenarios. Extrapolating these trends to 2100 yields 430 EJ in the SCW and 780 EJ in the RCW scenarios, while in the Stabilizing Policy cases there is 20% and 35% lower demand, respectively.

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[3] 1 EJ = 0.948 quadrillion BTU (Quad).

FIGURE 5-6

END-USE FUEL DEMAND BY REGION

(Exajoules)

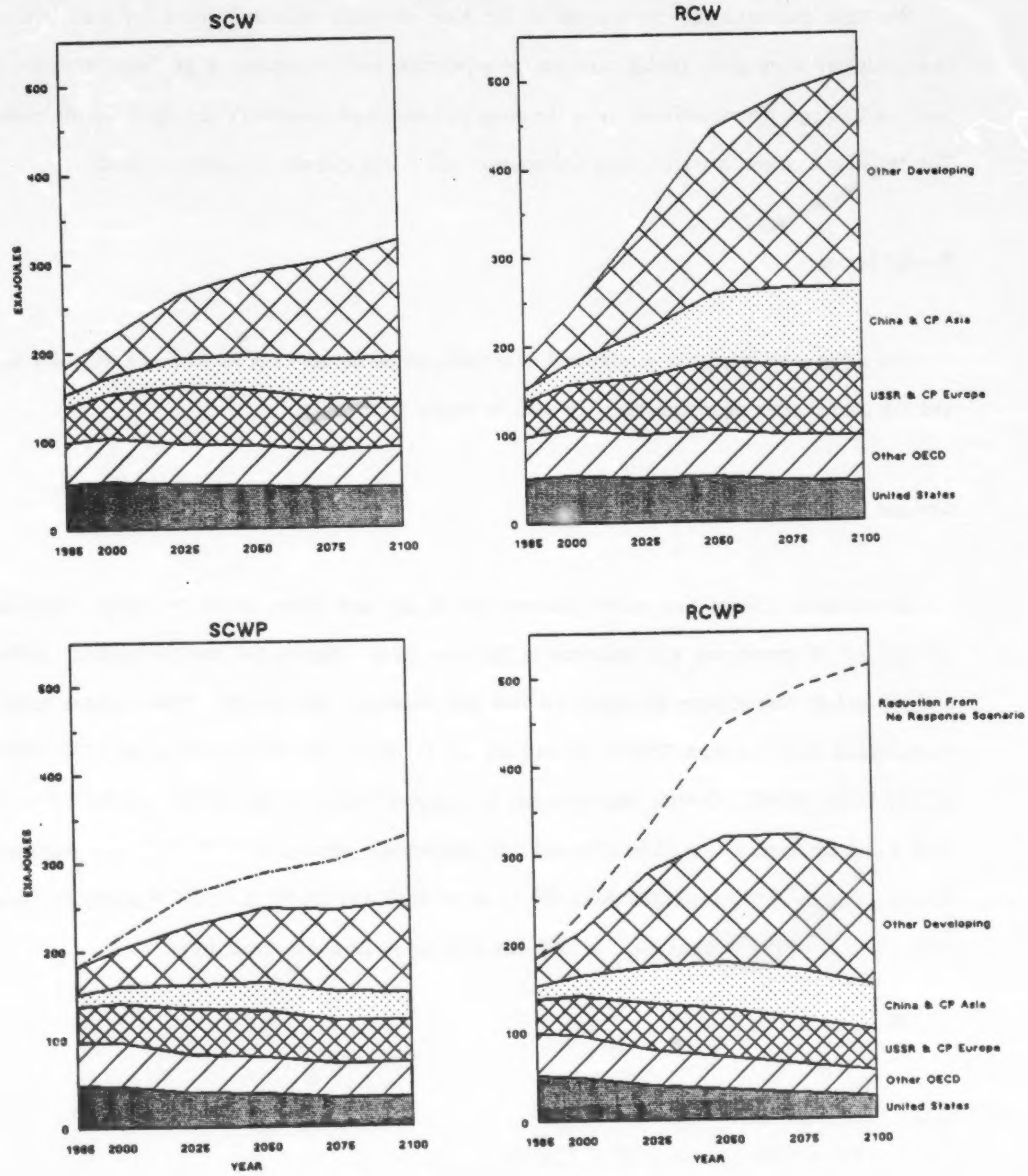
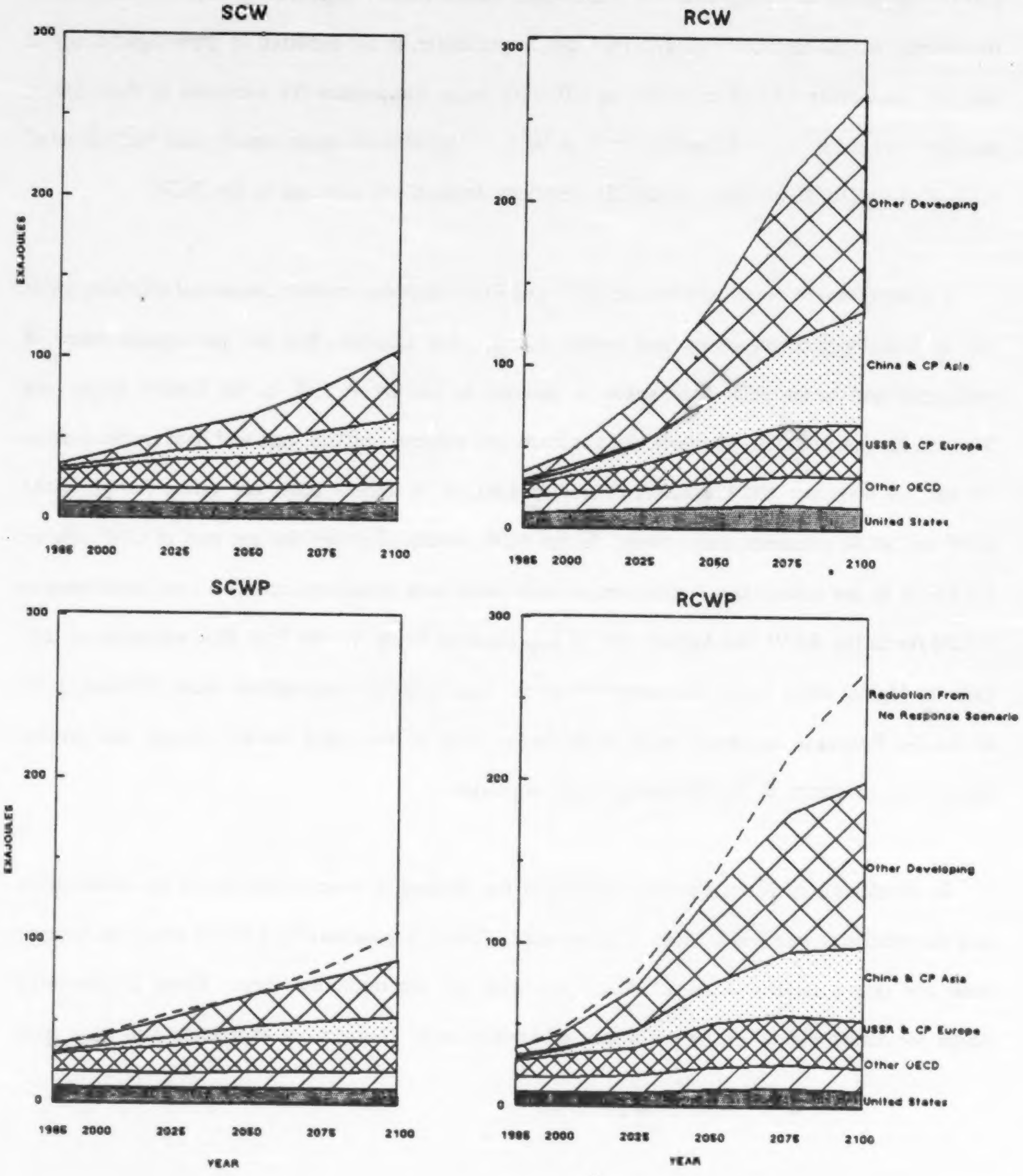


FIGURE 5-7

END-USE ELECTRICITY DEMAND BY REGION

(Exajoules)



In each scenario the growth in end-use demand is driven almost entirely by countries outside the OECD (USSR, Eastern Europe, China, and other developing countries) as a result of higher rates of economic and population growth in these regions and from more rapid efficiency improvements and the saturation of energy-intensive technologies in the OECD (e.g., steel production, automobile transportation, and central heating). Fuel use, in particular, is not expected to grow significantly in the U.S. and other OECD countries as efficiency gains compensate for increases in floor space, mobility, and production. Electricity use is projected to grow much more rapidly than fuel use in all cases, and significant increases in OECD electricity demand are reflected in the RCW.

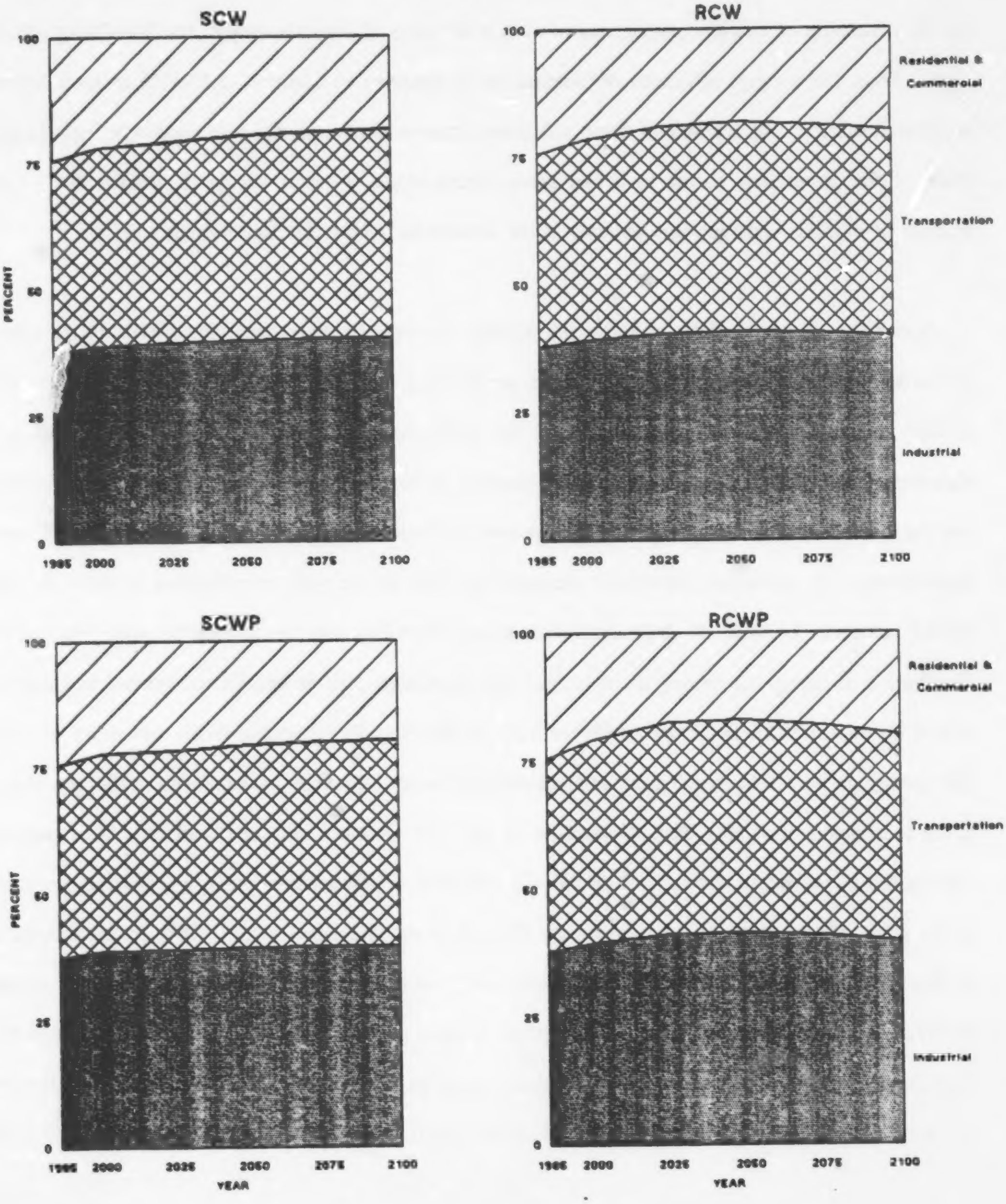
It is important to note that both the SCW and RCW scenarios assume substantial efficiency gains due to technological innovation and market forces. For example, fuel use per square meter of residential and commercial floor space is assumed to fall by 45-55% in the United States and Western Europe by 2025. Similarly, fleet average fuel efficiency of U.S. cars and light trucks reaches 7.8 and 6.9 liters per 100 kilometers (liters/100 km), or 30 and 34 miles per gallon (mpg), in the SCW and RCW scenarios, respectively. In the SCW, industrial energy use per unit of GNP falls by 1.5-2%/yr in the industrialized countries, in accordance with recent trends. This rate accelerates to 2-3.5%/yr in the RCW, the highest rate of improvement being for the East Bloc countries as they have the highest initial industrial energy intensities. Less optimistic assumptions about efficiency gains in the No Response scenarios would imply higher rates of associated climatic change and greater relative improvement in the Stabilizing Policy scenarios.

In developing countries the use of biofuels for cooking is strongly influenced by urbanization and the efficiency with which these fuels are used. Urban populations have better access to modern fuels and thus a smaller share of urban households will use traditional fuels. There is substantial scope for improvement of the efficiency of biomass use. Laboratory experiments in Asia with improved cookstoves suggest that it is possible to achieve efficiencies of up to 33% (compared with current averages of 8%). However, experience from the last decade of improved cookstove dissemination projects suggests that efficiencies are unlikely to exceed 20% in the field. We assume the dissemination of efficient cookstoves to almost all users of biomass only in the Stabilizing Policy cases. Thus, the average efficiency of biomass use is assumed to improve to 15-17% in each region in these scenarios. As a result of these efficiency improvements and because an increasingly larger share of the population moves to urban areas, where there is better access to modern fuels, the amount of biofuels consumption declines in the household sector for each scenario.

Important structural shifts underlie the aggregate trends in these scenarios. Electricity's share of end-use consumption more than doubles in the RCW, from 16% in 1985 to 19% in 2025 and 34% in 2100, while it grows less dramatically in the SCW, reaching 24% in 2100. These trends are accentuated in the policy scenarios as there appears to be even greater room for reductions in fuel use than in electricity use, partly because electricity is substituted for fuel in some highly-efficient applications. In particular, electricity accounts for 40% of end-use consumption by 2100 in the RCWP scenario because of dramatic increases in electricity use in developing countries. The distribution of energy use among the industrial, transportation, and residential and commercial sectors also shifts significantly, as shown in Figure 5-8. In the Rapidly Changing World the share of end-use energy going to the residential and commercial sectors declines continuously, while the share going to industry increases until the middle of the 21st Century and then declines. This pattern reflects the increasing importance of developing countries, which generally have low heating demands and a greater percentage of modern energy devoted to the industrial sector. This occurs despite a decline in the share of commercial energy use, particularly electricity, going to the industrial sector within developing country regions. As the most intense phase of industrialization is completed the transportation sector begins to take off, its share rising steadily after 2025. In the SCW scenario the share of end-use energy consumed in the industrial sector grows less dramatically and does not peak

FIGURE 5-8

SHARE OF END-USE ENERGY DEMAND BY SECTOR
(Percent)



until 2075 as industrialization in developing countries is stretched out over a longer time-span and dramatic increases in mobility are delayed. In the Stabilizing Policy scenarios the growth in transportation energy use is suppressed by much higher fuel efficiency and the share of end-use energy going to the residential and commercial sectors increases toward the end of the next century.

Primary Energy Supply

While policies affecting demand will have the largest impact on near-term greenhouse gas emissions, changes in the supply mix will also be very important over the long term. Global primary energy supply is shown by source for the four scenarios in Figures 5-9 and 5-10. Growth in primary energy production is substantially higher than growth in end-use energy consumption because of increased requirements for electricity and synthetic fuel production. This is most dramatic in the RCW, where primary energy production increases from 290 EJ in 1985 to 580 EJ in 2025 and 1410 EJ in 2100; a 100% and 380% increase, respectively, compared with 90% and 260% increases in end-use consumption.

The use of synthetic fuels to supplement conventional oil and gas production becomes particularly important after 2025, influencing both total requirements and the mix of sources (Figure 5-11). In the RCW conventional oil and gas production increases through 2050, then begins to decline due to resource depletion (the share of primary energy supplied by oil and gas declines throughout the projection period). As a result, synthetic fuels are increasingly relied on to supply liquid and gaseous fuel requirements. By 2050 19% of primary energy is used in synthetic fuels production, and this value increases to 40% by 2100. In the SCW heavy dependence on synthetic fuels begins later because conventional oil and gas resources are depleted more gradually. Coal is the dominant feedstock for synfuel production in both of these scenarios.

FIGURE 5-9

PRIMARY ENERGY SUPPLY BY TYPE

(Exajoules)

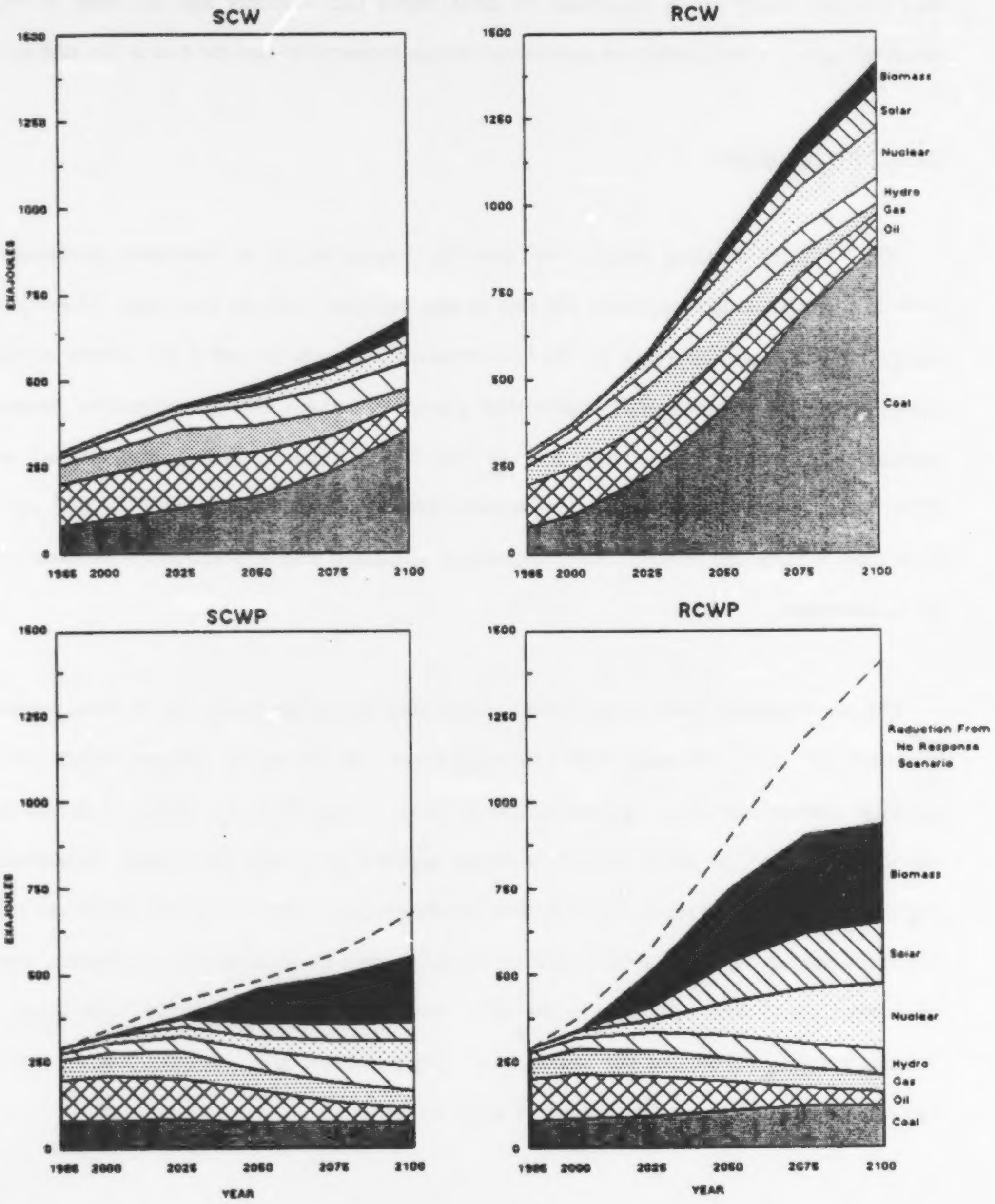


FIGURE 5-10

SHARE OF PRIMARY ENERGY SUPPLY BY TYPE
(Percent)

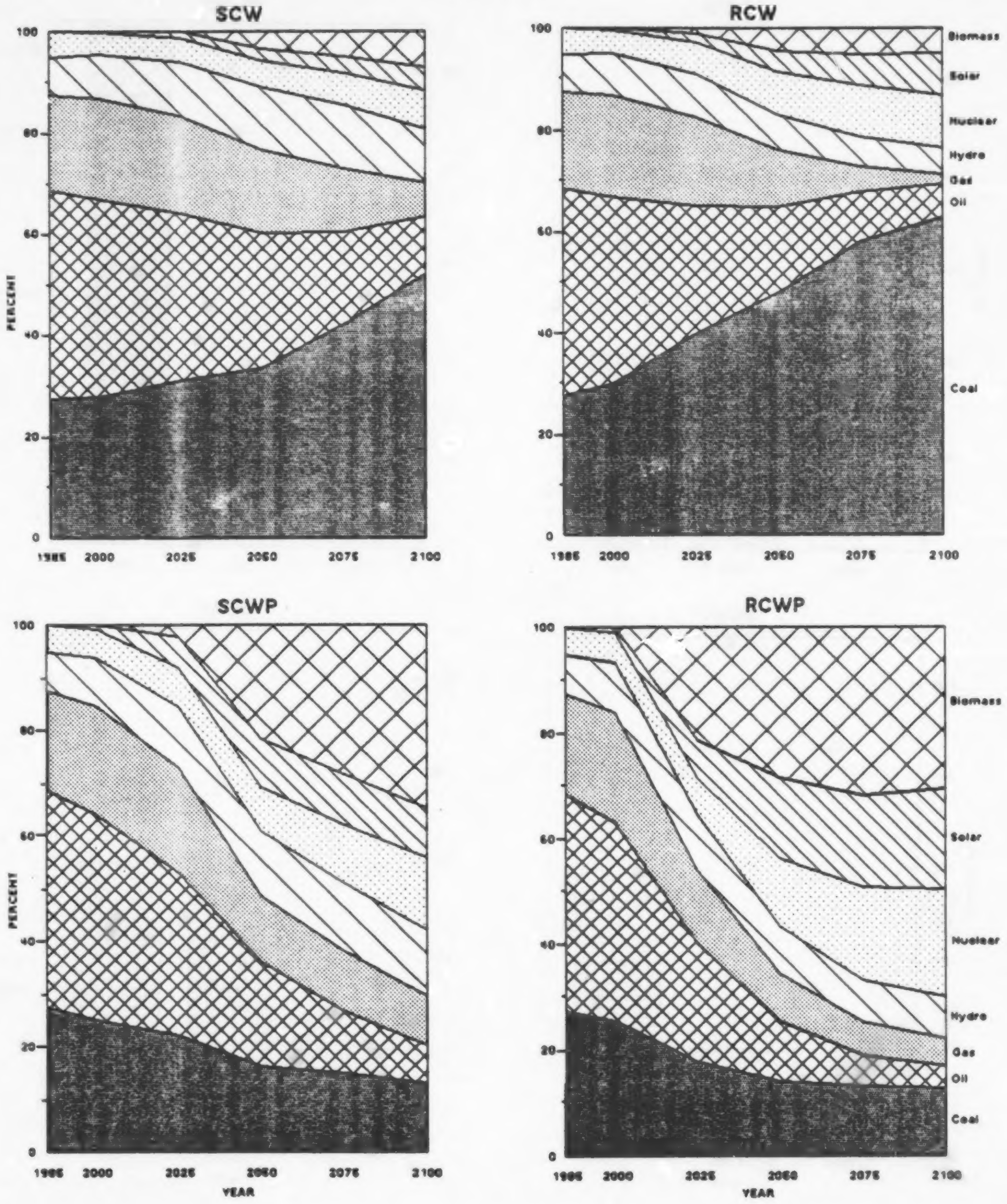
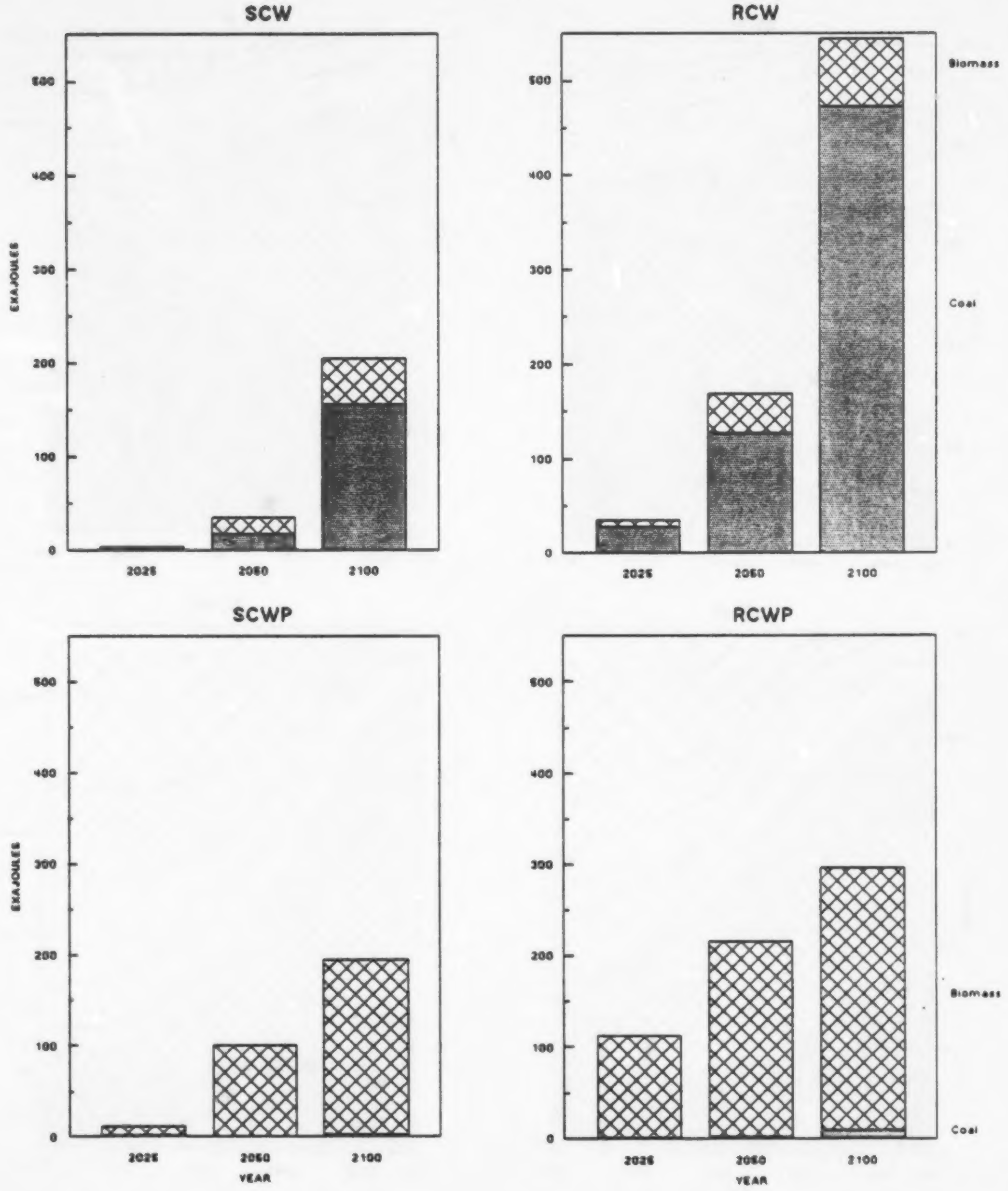


FIGURE 5-11

ENERGY DEMAND FOR SYNTHETIC FUEL PRODUCTION
(Exajoules)



The mix of primary energy resources used to generate electricity is also crucial in determining future greenhouse gas emissions. While non-fossil energy sources (nuclear, solar, and hydro) increase their absolute contribution to primary energy supply in all scenarios, in the absence of policies to limit greenhouse gas emissions, it is likely that future electricity production will be dominated by coal-based technologies over the long term (in the near term, current gas prices make gas-based combustion turbine technology very attractive in many regions). Thus in the RCW, demand for electricity and synfuel production pushes global coal consumption up by more than a factor of 10 between 1985 and 2100. Correspondingly, the share of primary energy supplied by coal increases from 27% in 1985 to 40% in 2025 and 63% in 2100 (Figure 5-10). The same forces are at work in the SCW, but the results are less dramatic: Coal production increases by less than a factor of 5, and its share of primary energy reaches just over 50% by 2100.

In the Stabilizing Policy scenarios natural gas is relied on more heavily in the near term while accelerated research and development and other incentives are assumed to make several non-fossil electricity supply technologies strongly competitive over the long term. In particular, photovoltaics, biomass-based combustion turbines, and advanced nuclear reactors appear to be strong candidates to make a large contribution to future electricity production (these and other options are discussed in some detail in Chapter VII). In the policy scenarios these technologies begin to supply energy after 2000 and become strongly competitive by 2025. By 2050 they supply 60% and 70% of global electricity in the SCWP and RCWP scenarios, respectively.[4] It is also assumed that research priorities and other policies promote the use of biomass-derived fuels rather than coal-based synfuels. In fact, in 2025 and 2050 total synfuel production is higher in the policy scenarios because biomass production and conversion is assumed to become competitive with imported oil and gas in many developing regions starting around 2010 (Walter, 1988). The particular mix among the non-fossil supply technologies shown in Figure 5-10 is rather arbitrary, but the type of non-fossil technologies is of little consequence to total greenhouse gas emissions.

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[4] This value includes all of the electricity generated from gas, reflecting the assumption that a little over half of the synthetic gas generated from biomass is actually both produced and consumed in integrated gasifier-combustion turbine units.

Greenhouse Gas Emissions From Energy Production and Use

The heavy reliance on coal in both the SCW and RCW scenarios leads to large increases in both CO_2 and CH_4 emissions (see Figures 5-14 and 5-16 later in the chapter). In the SCW energy-related emissions of CO_2 increase from 5.1 petagrams of carbon (Pg C) in 1985 to 7.2 Pg C in 2025 and 11.1 Pg C in 2100.[5] Emissions reach more than twice this level in the RCW scenario: 10.3 and 24.4 Pg C in 2025 and 2100, respectively. This growth in emissions of 0.5 Pg C per decade in the SCW and 1.3 Pg C per decade in the RCW between 1985 and 2025 compares with average growth of 1.1 Pg C per decade between 1950 and 1980. Emissions of CH_4 from fuel production, predominantly coal mining, grow even more dramatically. The estimated emissions from fuel production in 1985 are 60 teragrams of CH_4 (Tg CH_4) or just over 10% of the total.[6] In the SCW this source increases to 86 Tg CH_4 in 2025 and 160 Tg CH_4 in 2100. The corresponding values for the RCW are 130 Tg CH_4 in 2025 and 360 Tg CH_4 in 2100, about 20% and 30% of the CH_4 total, respectively.

The combination of higher efficiency and greater reliance on non-fossil fuels assumed in the Stabilizing Policy scenarios serves to substantially curtail CO_2 and CH_4 emissions. In both the SCWP and RCWP cases CO_2 emissions from energy use reach only 5.5 Pg C in 2025, after which time they decrease, reaching 3.2 and 4.3 Pg C by 2100 in the two cases, respectively. Similarly, CH_4 emissions from fuel production remain relatively constant in both of these scenarios.

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[5] 1 petagram = 10^{15} grams.

[6] 1 teragram = 10^{12} grams.

Energy-related emissions, other than of CO_2 and CH_4, are strongly affected by the type of control technology employed in addition to the total amount and type of energy used. Emissions of CO and NO_x associated with energy use can be expected to increase almost as rapidly as primary energy consumption in the absence of new policies. On the other hand, in the Stabilizing Policy scenarios NO_x emissions are roughly constant and CO emissions are cut by more than half. This assumes that the rest of the world gradually adopts control technology similar to that required of new mobile and stationary sources in the United States today, and that industrialized countries adopt standards consistent with the use of Selective Catalytic Reduction technology in utility and industrial applications after 2000, with developing countries following after 2025.

Comparison to Previous Studies

Despite the large range of outcomes illustrated by the four scenarios developed here, none of the global rates of change are unprecedented (Table 5-3). Global reductions in aggregate energy intensity generally fall within the range of 1-2% per year; the lower value is consistent with long-term trends and the higher value is consistent with recent experience. Reductions in the amount of carbon emitted per unit of energy consumed (carbon intensity) varies from 0.0-1.3% per year with significant declines only apparent in the Stabilizing Policy cases. These values are not unprecedented as carbon intensity declined by an average of 1.5% per year between 1925 and 1985 due to increased reliance on oil and gas over coal.

While we know of no previous attempts to develop long-term scenarios for emissions of the full set of gases discussed above based on explicit economic and technological assumptions, there have been a number of previous studies that relate to many of the components examined here. Over the

TABLE 5-3

Key Global Indicators

Parameter	Scenario[a]	Year 1985	 2025	 2100
GNP/capita (1000 1988 $)	SCW, SCWP	3.0	3.7	7.1
	RCW, RCWP		6.7	35.6
Primary Energy (EJ)[b]	SCW	290	430	680
	RCW		580	1410
	SCWP		380	550
	RCWP		520	940
Fossil Fuel CO_2 (Pg C)[c]	SCW	5.1	7.2	11.1
	RCW		10.3	24.4
	SCWP		5.5	3.2
	RCWP		5.5	4.3

Parameter	Scenario	1985-2025	2025-2100
GNP/capita (%/yr)	SCW, SCWP	0.5	0.9
	RCW, RCWP	2.0	2.3
Energy/GNP (%/yr)	SCW	-1.1	-0.8
	RCW	-1.6	-1.4
	SCWP	-1.3	-1.0
	RCWP	-1.9	-1.8
Fossil Fuel CO_2/Energy (%/yr)	SCW	-0.1	-0.0
	RCW	0.0	-0.0
	SCWP	-0.5	-1.2
	RCWP	-1.3	-1.1

[a] SCW = Slowly Changing World; SCWP = Slowly Changing World with Stabilizing Policies; RCW = Rapidly Changing World; RCWP = Rapidly Changing World with Stabilizing Policies.

[b] EJ = exajoule = 0.948 quadrillion BTUs

[c] Pg C = petagrams of carbon; 1 petagram = 10^{15} grams.

last decade there have been many studies of U.S. energy futures that can be compared to our U.S. results. In addition there have been several recent studies of long-term global energy use and CO_2 emissions (Chapter I). One recent study has developed "conventional wisdom reference scenarios" for CH_4, CO, NO_x, and N_2O emissions related to major energy sources (Darmstadter et al., 1987). This section compares the scenarios presented here to those developed in previous work.

Since the OPEC oil embargo focused the world's attention on energy in 1973 a number of studies have examined the future of energy supply and demand in the United States. Those analyses contain much more detail, particularly in the short term, than is possible in this study, as our focus is necessarily global and long term. Nonetheless, it is useful to compare the results of this study for the U.S. with selected previous work. The National Energy Policy Plan (NEPP) prepared by the Department of Energy (U.S. DOE, 1987b) and *Energy for A Sustainable World* (ESW), an international study supported by the World Resources Institute (Goldemberg et al., 1985, 1987, 1988) are examples of two important recent studies.

The results of these studies for the United States are summarized and compared with our scenarios in Tables 5-4 and 5-5. A key point is that both of the No Response scenarios developed here incorporate much lower growth in energy use and CO_2 emissions than is projected in the NEPP reference and NEPP high-efficiency cases. The largest discrepancies are in demand for electricity and consumption of coal, although all energy sources other than gas and all sectors show higher consumption in the NEPP projections. The NEPP Reference Case projects an increase of almost 40% in U.S. CO_2 emissions between 1985 and 2010, while the High Efficiency case produces about a 20% increase. By contrast, the RCW scenario, which has GNP assumptions similar to those used in NEPP, estimates about a 10% increase in CO_2 emissions, while the SCW scenario predicts essentially flat emissions. Had the NEPP reference case been adopted as one of our No Response

TABLE 5-4

Comparison of No Response Scenarios and NEPP

		End-Use Energy Demand (exajoules)				
			Estimated for 2010			
Sector		1985	SCW[a]	RCW[b]	NEPP-RC[c]	NEPP-HE[d]
Residential/Commercial	Fuel	11	10	11	13	19[e]
	Elec	6	6	7	9	-
Transport	Fuel	21	21	19	23	22
	Elec	0	0	0	0	0
Industry	Fuel	18	20	21	26	28[e]
	Elec	3	3	4	7	-
Total	Fuel	50	51	51	58	51
	Elec	9	9	10	15	13

	Primary Energy Consumption (exajoules)				
		Estimated for 2010			
Primary Energy	1985	SCW	RCW	NEPP-RC	NEPP-HE
Coal	19	18	22	38	31
Oil	33	32	29	35	33
Gas	19	19	22	19	17
Other[f]	7	8	8	18	16
Total	77	77	82	110	97

	Carbon Dioxide Emissions (petagrams of carbon)				
		Estimated for 2010			
	1985	SCW	RCW	NEPP-RC	NEPP-HE
CO_2	1.3	1.3	1.4	1.8	1.6

[a] Slowly Changing World scenario.
[b] Rapidly Changing World scenario.
[c] National Energy Policy Plan (NEPP) Reference Case (DOE, 1987b)
[d] National Energy Policy Plan (NEPP) High Efficiency Case (DOE, 1987b)
[e] Fuel + Electricity. Separate values not given.
[f] Excludes dispersed wood.

TABLE 5-5

Comparison of Stabilizing Policy Scenarios and ESW

		End-Use Energy Demand (exajoules)				
			Estimated for 2020			
Sector		1985	SCWP[a]	RCWP[b]	ESW-S[c]	ESW-R[d]
Residential/ Commercial	Fuel	11	8	5	5	5
	Elec	6	5	5	4	4
Transportation	Fuel	21	15	12	12	14
	Elec	0	0	0	0	0
Industry	Fuel	18	18	21	14	15
	Elec	3	3	4	5	5
Total	Fuel	50	41	38	31	34
	Elect	9	8	9	9	9

	Primary Energy Consumption (exajoules)				
		Estimated for 2020			
Primary Energy	1985	SCWP	RCWP	ESW-S	ESW-R
Coal	19	11	9	11	13
Oil	33	24	18	13[e]	14[e]
Gas	19	18	22	13[e]	14[e]
Other	7	12	18	14	14
Total	77	65	64	52	56

	Carbon Dioxide Emissions (petagrams of carbon)				
		Estimated for 2020			
	1985	SCWP	RCWP	ESW-S	ESW-R
CO_2	1.3	1.0	0.8	0.7	0.8

[a] Slowly Changing World with Stabilizing Policies.
[b] Rapidly Changing World with Stabilizing Policies.
[c] Energy for a Sustainable World, Goldemberg et al., 1987, 1988. Assumes a 50% increase in per capita GNP from 1980 to 2020. Note that the SCWP case assumes a 50% increase from 1985 to 2020.
[d] Energy for a Sustainable World, Goldemberg et al., 1987, 1988. Assumes a 100% increase in per capita GNP from 1980 to 2020. Note that the RCWP case assumes a 120% increase from 1985 to 2020.
[e] Given as Oil + Gas. A 50% split is assumed following the global supply scenario given by Goldemberg et al., 1987, 1988.

scenarios, the U.S. contribution to global emissions would have been substantially higher than what we have estimated in the SCW and RCW cases, and the difference between the No Response and Stabilizing Policy cases would have been significantly greater.

Comparing low emissions scenarios, U.S. energy use is considerably higher in the Stabilizing Policy cases than in those given in *Energy for a Sustainable World*. The largest differences in consumption are in the industrial sector, with significant differences also in the residential and commercial sectors in the slow-growth cases. We assume that slower turnover of the housing stock leads to higher residential and commercial demand in the slow growth variant, whereas Goldemberg et al. assume that income does not effect demand in this sector. Despite higher energy consumption in our scenario, the two rapid-growth cases have similar CO_2 emissions due to lower consumption of coal and heavier reliance on gas and non-fossil energy sources in the RCWP scenario compared with the ESW cases.

The global energy use and CO_2 emissions calculated for 2050 in the four scenarios developed here are compared to the bounding extrapolations discussed in Chapter IV and the results of selected previous studies in Table 5-6. The total energy use derived in our scenarios falls within the lower end of the range given by trend extrapolation and previous analyses. In those studies that included a "Base Case" that did not assume the implementation of policies to reduce CO_2 emissions, the estimated primary energy demand for the year 2050 ranges from 21 to 52 terawatts (TW)[7]. This level of energy demand is approximately 2.2 to 5.5 times 1985 consumption levels of 9.4 TW. The Rapidly Changing World scenario has total energy demand that is quite similar to the Base Case given by a number of previous studies, including Edmonds and Reilly (1984), Seidel and Keyes (1983), and World Energy Conference (1983). The Slowly Changing World scenario, with almost 50% less

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[7] 1 terawatt = 10^{12} watts = 31.54 EJ per year.

TABLE 5-6

Summary of Various Primary Energy Forecasts for the Year 2050

Report	"Base Case" TW	Range TW	"Base Case" Pg C/yr	Range Pg C/yr
This Study, No Response cases	-	15.3-28.3	-	7.6-14.9
This Study, Stabilizing Policy cases[a]	-	14.6-23.7	-	4.4-5.1
Trend Extrapolation (Chapter IV)		10-130	-	19-240
Darmstadter et al. (1987)	35.1		22.2	
Edmonds and Reilly (1983)[a]	52.2	--	26.3	15.7-26.3
Edmonds and Reilly (1984)	28.4	17-63	14.5	6.8-47.4
Edmonds and Reilly (1986)[b]	21.3	12.7-38.8	7.7	4.3-18.7
Goldemberg et al. (1985)[a]	11.2 (2020)	11.2-14.8 (2020)	4.6 (2020)	4.6-5.9 (2020)
IIASA (1981)	-	22.4-35.7 (2030)	-	10-17 (2030)
IIASA (1983)	26.3	--	9.4	
Keepin et al. (1986)	-	10-35	-	2-20
Legasov et al. (1984)	42	--	13	
Lovins et al. (1981)[a]	4.6	--	<1 (2030)	
Nordhaus and Yohe (1983)[c]	30.6	18.1-43.1	13.9	7.2-20.6
Reister (1984)	29.9	24.0-41.3	10.7	9.7-27.1
Rose et al. (1983)[a]	-	16.3-32.3	-	2.7-15
Seidel and Keyes (1983)[a]	30.0	--	15	10-18
World Energy Conference (1983)	29.8	18.9-29.8	14.4	10.0-14.4

[a] Policies to limit CO_2 emissions are explicitly considered in some or all of these cases.

[b] Median, 25th and 75th percentile, non-zero correlation between parameters.

[c] Probability weighted mean ± one standard deviation.

Source: Adapted from Keepin et al. (1986). See text, Chapter I, and original source for further discussion and notes.

total energy use in 2050, lies between the median and 25th percentile non-zero correlation scenario of Edmonds et al. (1986) and Reilly et al. (1987). The estimated uncertainty bounds in the systematic uncertainty analysis conducted by Edmonds et al. are not symmetric; their median scenario has significantly lower energy use and CO_2 emissions than both the mean of their results and the result of using the median values for all model parameters. The implication is that very high energy use scenarios may be much less probable than is suggested by simply considering the range given by many studies.

Compared with the energy use estimates there is substantially less, though still considerable, variation in the CO_2 emissions estimates for 2050. None of the studies cited in Table 5-6 approach within a factor of four the result of exponentially extrapolating the pre-1973 rates of energy demand growth, assuming no change in the mix of sources. This reflects the constraint due to the finite size of the fossil fuel resource base (Chapter IV), which implies that very high growth in energy consumption would have to be accompanied by a significant shift away from fossil fuels (but not before atmospheric CO_2 concentrations reached extraordinarily high levels). Considering the full range of values for both energy use and CO_2 emissions represented in Tables 5-4 and 5-5, it does appear that, as intended, the Slowly Changing and Rapidly Changing World scenarios represent very different but not extreme possibilities.

While the general agreement found between this study and previous studies at the aggregate level may be comforting, substantial disagreements are possible when the results are examined more closely. For example, the global increase in energy demand obtained in the Rapidly Changing World scenario is the result of almost level demand in OECD countries coupled with very vigorous demand growth in developing countries. Other scenarios with nearly identical global demand in 2050 may not distinguish among regions (e.g., Nordhaus and Yohe, 1983) or may have a more even pattern of energy demand growth (e.g., Edmonds and Reilly, 1984). Similarly, the GNP growth rate assumed in the RCW scenario is higher than what was assumed by Seidel and Keyes (1983), but because higher rates of technical efficiency improvements were assumed in the RCW case, energy demand and CO_2 emissions are almost identical in 2050.

The results obtained in the policy scenarios developed here are most appropriately compared with the results of Lovins et al. (1981), Rose et al. (1983), and Goldemberg et al. (1985, 1987, 1988). These studies all emphasize the possibility that increased efficiency of energy use could limit energy demand and CO_2 emissions while allowing for sustainable economic growth. They conclude that energy demand in 2050 could be held to between 5 and 16 TW by supplying energy services with advanced cost-effective technology that is either available or nearly commercial today. In these scenarios efficiency improvements combined with shifts in energy supply allow CO_2 emissions to be held at or below today's level, and Lovins et al. (1981) argue that it is technically feasible to reduce fossil fuel CO_2 emissions by about 80% over 50 years. The SCWP and RCWP scenarios have energy consumption of 15 and 24 TW respectively--similar to, but somewhat higher than, what previous studies suggested was feasible. Part of this difference may be explained by the high rate of economic growth assumed in the RCWP case and, particularly in comparison to Lovins et al., our assumption that efficiency measures are not adopted up to their technical potential. The CO_2 emissions in the policy scenarios are 10-20% below current levels, again consistent with some previous analyses. This result is obtained in different ways, however. For example, the lowest CO_2 scenario given by Rose et al. assumes substantially more contribution from non-fossil energy sources than do the policy scenarios developed here, while the Goldemberg et al. high demand scenario has somewhat more oil and gas and less coal than does the RCWP case in 2020.

The estimates of energy-related (fossil fuel and wood use) emissions of CH_4, N_2O, NO_x, and CO developed here are compared in Table 5-7 with results of a study by Darmstadter et al. (1987). While the main purpose of their study was to develop an historical database, reference values for future emissions are presented assuming either constant emission coefficients or coefficients declining by 1% per year. The emissions calculated with constant coefficients by Darmstadter et al. increase much more rapidly than those obtained in any of our scenarios. These differences are not too surprising given our explicit assumptions regarding technological change, including increasing penetration of emission control technologies. The largest discrepancy is for N_2O, reflecting not only our assumptions regarding technical change, but also the much higher initial emission coefficient adopted by Darmstadter et al. based on Hao et al., 1987 (see Chapter II). The initial estimate of CO emissions given by Darmstadter et al. is a factor of two lower than ours, probably due primarily to their extrapolation of the U.S. emission coefficient for gasoline to the rest of the world; we have attempted to account for variations in automobile emission control technology by region, with most regions having higher average CO emissions than the U.S. The closest agreement is for CH_4, probably because these emissions are directly proportional to the total quantity of coal and gas produced, and are not assumed to depend on production technology in our No Response scenarios.

When Darmstadter et al. assume that all emission coefficients decline by 1% per year, they obtain estimates of NO_x emissions that are similar to those occurring in the RCW case and CH_4 emissions estimates closer to those obtained in the RCWP case; their CO emissions estimate falls between these two cases. Overall, the RCWP case has significantly lower emissions than are obtained by Darmstadter et al. even when they decrease their emission coefficients by 1%/y for a full century. This is a result not only of the assumptions regarding emission control technology, but also because our policy scenarios have substantially lower total energy demand and a very different fuel mix.

TABLE 5-7

Comparison of Energy-Related Trace-Gas Emissions Scenarios

		Emissions of Trace Gases (teragrams)		
Trace Gas	Scenario	1985/1980	2025/2030	2075/2080
CH_4	RCW	68	141	301
($Tg\ CH_4$)	RCWP		73	74
	* Darmstadter et al.	63	192	432
	** Darmstadter et al.		117	131
N_2O	RCW	1.1	2.1	3.8
(Tg N)	RCWP		1.2	1.4
	* Darmstadter et al.	4.3	16	57
	** Darmstadter et al.		9.5	21
NO_x	RCW	25	43	77
(Tg N)	RCWP		27	21
	* Darmstadter et al.	20	62	184
	** Darmstadter et al.		37	68
CO	RCW	202	318	651
(Tg C)	RCWP		122	82
	* Darmstadter et al.	108	292	614
	** Darmstadter et al.		177	226

* Constant Emission Coefficients.

** Emission Coefficients Decline 1% Per Year.

Industrial Processes

Halocarbon Emissions

The most important industrial source of greenhouse gases not directly associated with energy use is the production and release of CFCs and halons. In both the Slowly Changing World and Rapidly Changing World scenarios, the Montreal Protocol as currently formulated is assumed to come into force and apply throughout the projection period. This agreement (described in Chapter IV, VIII, and IX) calls on developed countries to reduce their emissions of certain CFCs 50% from 1986 levels by 1998, and to freeze the use of halons. Developing countries with low per capita consumption, however, are allowed to increase the use of these compounds for up to 10 years--as a result, emissions of the controlled compounds could actually increase substantially, depending on the number of countries that participate in the Protocol and the rate at which use increases in developing and non-participating nations (Hoffman and Gibbs, 1988). For the Slowly Changing World scenario we adopt the assumptions of the Protocol scenario developed for the Regulatory Impact Assessment of rules to implement the Montreal Protocol in the United States (U.S. EPA, 1988). Namely that, in addition to the U.S., 94% (in terms of current CFC consumption) of developed countries and 65% of developing countries participate in the agreement. In this scenario the global average annual growth rate in demand for products and services that would use CFCs, if they were available, is approximately 4.0% from 1986 to 2000 and 2.5% from 2000 to 2050 (constant production is assumed after 2050). Growth in demand is much higher in certain developing countries, particularly India and China. These growth rates are not applied directly to CFC use in non-participating and developing countries, however, because it is assumed that shifts in technology development away from CFCs in the United States and other participating countries "rechannels" demand in other countries as well.[8] The Stabilizing Policy scenarios assume that the Montreal Protocol is strengthened to produce a complete phase-out of CFCs in participating countries by 2003.[9]

Figure 5-12 shows the estimates for emissions of CFC-11, -12, and -13, and HCFC-22 under the four scenarios. Emissions change more slowly than production because a significant portion of each year's production is "banked" in air conditioners, refrigeration systems, and closed-cell foams. The model keeps track of the size of this bank and estimates the gradual release of these CFCs. In the Slowly Changing World scenario emissions are relatively constant despite the Protocol's requirement of a 50% reduction in participating industrialized countries. After declining to 12% below 1985 levels between 1990 and 2020, emissions of CFC-11 begin to rise again, reaching 1985 levels by the end of the projection period. CFC-113 emissions also fall significantly for a few decades but rise again toward 1985 levels. CFC-12 emissions never decline to 1985 levels: they decline by 11% between 1990 and 2015, reaching a few percent above 1985 values, then they rise slowly, almost reaching the 1990 peak levels towards the end of the 21st Century. Emissions of HCFC-22 grow rapidly as a substitute for the fully-halogenated species that have the highest ozone-depletion potential. Although HCFC-22 has a shorter lifetime and weaker radiative forcing than the fully-halogenated compounds, it could make a significant contribution to global warming during the next century because it is not controlled by the Montreal Protocol.

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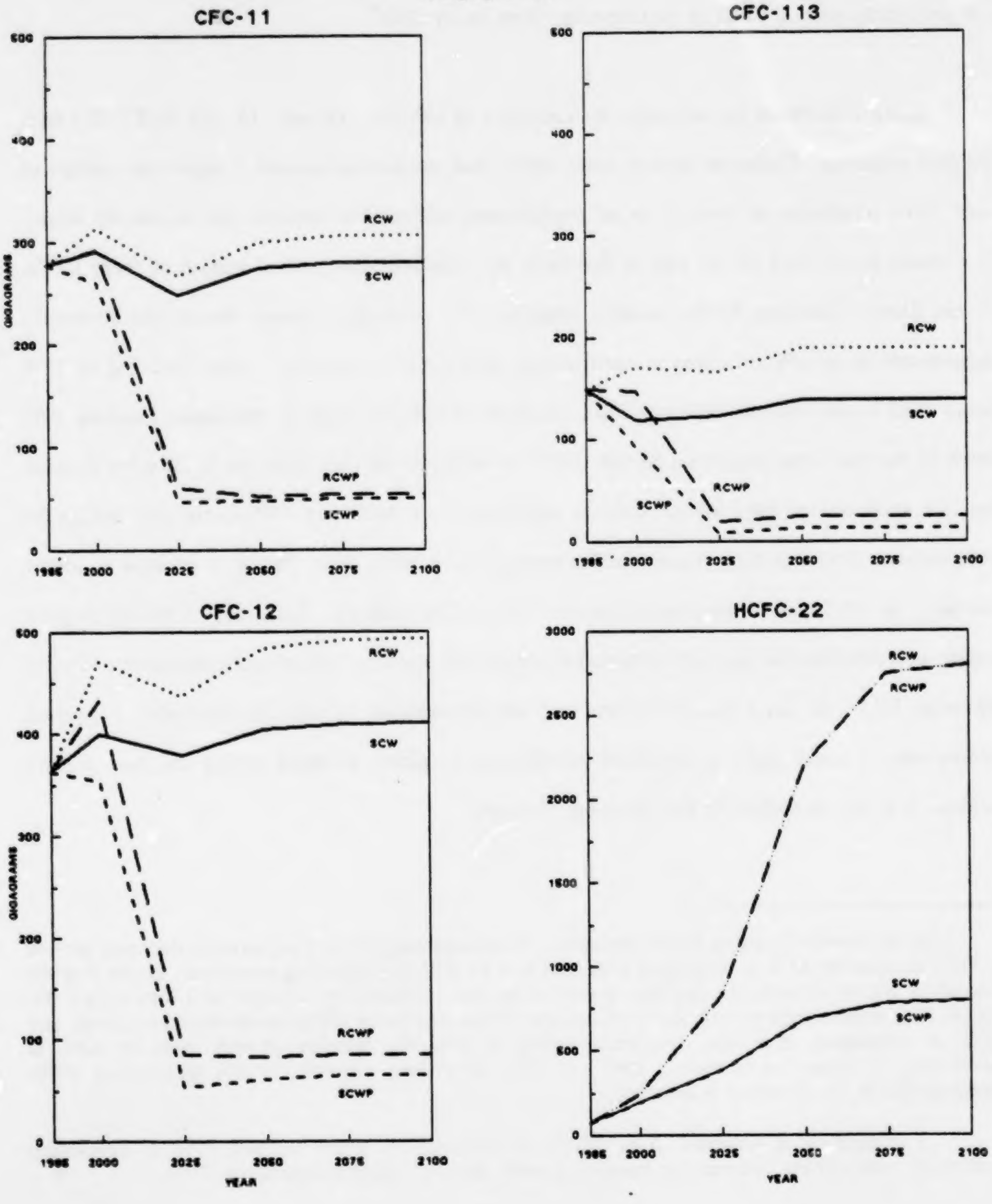
[8] In the Slowly Changing World scenario this rechanneling effect is assumed to decrease growth in CFC demand by 63% in developed countries and by 50% in developing countries. In the Rapidly Changing World scenario the baseline growth rates are increased by a factor of 1.7 to reflect the higher rate of economic growth, but participation is assumed to be 100% in developed countries and 75% in developing countries, and rechanneling reduces the baseline growth rates by 63% in developing countries (rechanneling does not affect developed countries in this scenario as 100% participation in the Protocol is assumed).

[9] Participation is assumed to be 100% in industrialized countries and 85% in developing countries; rechanneling reduces the baseline growth rates of non-participants by 75%.

FIGURE 5-12

EMISSIONS OF MAJOR CFCs
(Gigagrams)



In the RCW, higher growth rates in developing countries more than compensate for higher participation and rechanneling rates. CFC-11 emissions decline by no more than 6% below 1985 levels, while CFC-12 and -113 each increase by more than 25%. Emissions of HCFC-22 grow dramatically in this scenario. In the SCWP case emissions of the fully-halogenated compounds fall by more than 80% from 1985 levels by 2025, which is sufficient to reverse the trend in concentrations (see Figure 5-18). Emission reductions in the RCWP case are not quite as large, but still lead to declining concentrations after 2025. HCFC-22 emissions are assumed to be the same in the No Response and Stabilizing Policy cases; however, these emissions could rise as a result of a CFC phase-out if chemical substitution is the primary approach to eliminating CFCs, or fall, if product substitution and process redesign are the major approaches (see Chapter VI).

Emissions From Landfills and Cement

Other important activities included in the industrial category are CO_2 emissions from cement making and CH_4 emissions from landfills. The growth of these activities in developing countries is assumed to be related to per capita income in a simple fashion, although growth is curtailed as current per capita levels in industrialized countries are approached. The result is a three- to four-fold increase in CO_2 emissions from cement in the SCW and RCW scenarios, respectively, though emissions remain less than 0.5 Pg C/yr in all cases. Landfill CH_4 emissions increase by more than five-fold in the RCW, reaching 15% of the total by 2100. In the policy scenarios, advanced materials are assumed to reduce the demand for cement (relative to the No Response scenarios), while gas recovery systems and waste reduction policies are assumed to limit emissions from landfills. The result is that emissions from cement making still increase by a factor of two to three, but CH_4 emissions from landfills are held essentially constant.

Changes in Land Use

Deforestation has been a significant source of CO_2 to the atmosphere over the last two centuries, as clearly shown by the measurements of CO_2 concentrations in Greenland and Antarctic ice (Chapter II). If current trends continue, tropical forests could be completely eliminated during the next century, adding significantly to the CO_2 emissions from fossil fuels. On the other hand, efforts are underway to reverse deforestation; if these efforts succeed, reforestation could become a net sink for atmospheric CO_2. The total amount of carbon that can move in either direction between the atmosphere and terrestrial ecosystems is ultimately constrained by the area of forests available for deforestation or by the area of land available to support new forests. The timing and magnitudes of these fluxes of carbon are determined by the timing and extent of changes in land use as influenced by local, national, and international policies.

The causes of deforestation are complex and vary from country to country. This makes it difficult to directly tie assumptions about deforestation rates to the economic and demographic assumptions of the general scenarios. Qualitatively, we assume that in a Slowly Changing World poverty, unsustainable agricultural practices, and rapid population growth lead to continuously increasing pressure on remaining forests. The rate of deforestation is assumed to increase from current levels at the rate of population growth and tropical deforestation increases from 11 million hectares per year (Mha/yr) in 1980 to 34 Mha/yr in 2047, when all the unprotected forests in Asia are exhausted. In a Rapidly Changing World improved agricultural practices and the substitution of modern fuels for traditional uses of wood could ease the pressure on forests. Nonetheless, clearing of forest lands for agriculture, pasture, logging, and speculation could continue apace, even if small areas are set aside as biological preserves. In this scenario tropical deforestation is assumed to increase very gradually, reaching 15 Mha/yr in 2097, before the unprotected forest areas of Latin America are exhausted.

In the Stabilizing Policy scenarios it is assumed that a combination of policies succeed in stopping deforestation by 2025, while more than 1000 Mha is reforested by 2100. Only land that once supported forests and is not intensively cultivated is assumed to be available for reforestation. These lands include 85% of the area currently involved in shifting cultivation (370 Mha) under the assumption that this practice is replaced by sustainable low input agriculture (Sanchez and Benites, 1987). In addition, fallow agricultural land in the temperate zone (250 Mha), planted pasture in Latin America (100 Mha), and degraded land in Africa and Asia (400 Mha) is assumed to be reforested. Of the reforested land, about 380 Mha is assumed to be in plantations (sufficient to produce the biomass energy requirements of the RCWP case with productivity increases expected by the Department of Energy; Walter, 1988), the rest absorbs carbon at a much lower rate but reaches a higher level of average biomass.[10]

The carbon fluxes associated with these deforestation/reforestation scenarios based on Houghton's (1988) low estimates of average biomass are shown in Figure 5-13. In the SCW CO_2 emissions from deforestation increase rapidly from 0.7 Pg C/yr to more than 2 Pg C/yr in 2047 before the Asian forests are exhausted. Latin American and African forests are exhausted by 2075, reducing emissions drastically. Total deforestation emissions are almost the same in the RCW but they are spread out over a longer period. Emissions are close to 1 Pg C/yr from 2000 to 2100. In the Stabilizing Policy scenarios the biosphere becomes a sink for carbon by 2000 and reaches its peak

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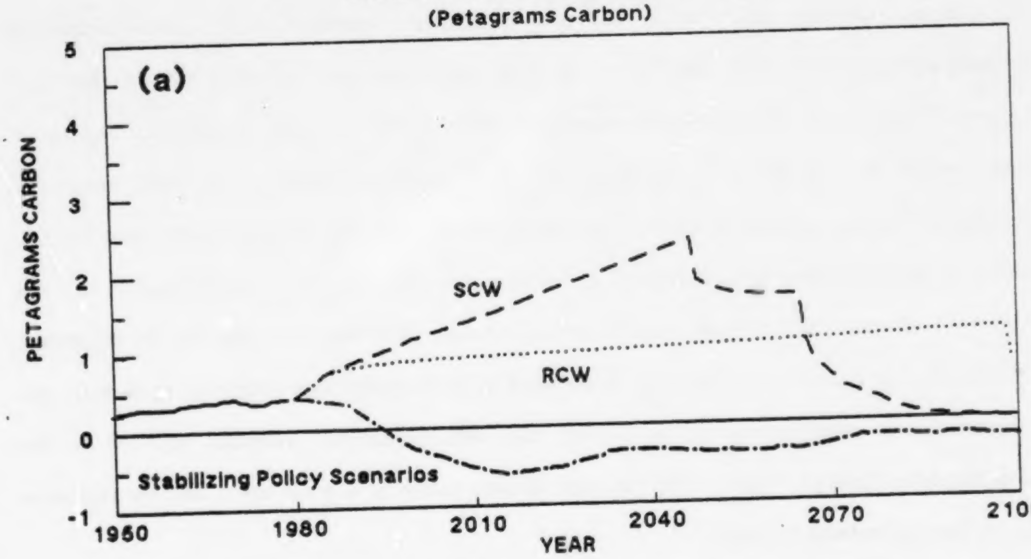
[10] Plantation products decay at various rates at the end of each rotation; no attempt to protect this carbon from oxidation is assumed.

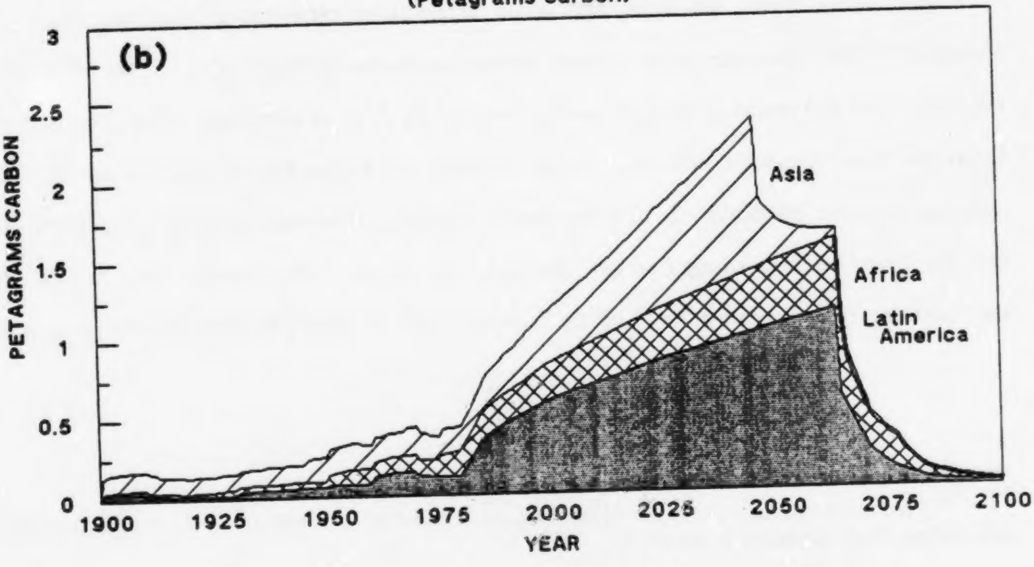
FIGURE 5-13

CO2 EMISSIONS FROM DEFORESTATION



CO2 From Deforestation
(Petagrams Carbon)

Slowly Changing World Scenario by Region
(Petagrams Carbon)



absorption of 0.7 Pg C/yr before 2025. The size of this sink declines gradually after 2025 as forests reach their maximum size and extent.

Agricultural Activities

The demand for agricultural products is a direct function of population, but is not strongly dependent on income levels. Thus, there are only small differences between the scenarios as the much higher incomes largely offset the somewhat lower populations in the RCW compared with the SCW. The land area used for rice production, and thus the methane emissions from this source, increases by only about 50% by 2100 in both the SCW and RCW scenarios (production per hectare increases by 80-100%). Meat production increases more, about 125%, as demand rises with income to some extent. Satisfying the demands of increasing populations with a finite amount of land requires more intensive cultivation, and fertilizer use increases by 160% as a result.

In the Stabilizing Policy scenarios we do not assume changes in the demand for agricultural commodities, but rather changes in technology and production methods that could reduce greenhouse gas emissions per unit of product. Although the impact of specific technologies cannot be estimated at present, a number of techniques have been identified for reducing methane emissions associated with rice and meat production and nitrous oxide emissions related to the use of fertilizer (Chapter VII). For simplicity, we have assumed that CH_4 emissions per unit of rice, meat, and milk production decrease by 0.5% per year (emissions from animals not used in commercial meat or milk production are assumed to be constant). Emissions of N_2O per unit of nitrogenous fertilizer applied are also assumed to decrease by 0.5% per year for each fertilizer type. In addition, fertilizer use is assumed to shift away from those types with the highest emissions after 2000. Based on these assumptions, CH_4 emissions from rice production remain roughly constant until 2075, after which time they fall by about 20% as the global population stabilizes. Methane emissions from enteric fermentation increase by 40-50% by the middle of the 21st Century, before falling to within about 30% of 1985 levels. Similarly, N_2O emissions from fertilizer increase from 0.3 to 0.5 Tg N/yr between 1985 and 2025 and then remain roughly constant.

Total Emissions

Total emissions of the key radiatively-important gases, the aggregate of estimates of the emissions from each activity discussed above and of natural emissions, are shown in Table 5-8. Overall, emissions increase gradually in the Slowly Changing World scenario and more dramatically in the Rapidly Changing World, while in the policy scenarios emissions are reasonably stable or declining.

In the No Response scenarios CO_2 emissions are projected to increase to a much greater extent than emissions of the other gases. This is because all net CO_2 emissions are assumed to be anthropogenic in origin and because CO_2 is a fundamental product of all fossil-fuel combustion. In the SCW increased deforestation contributes significantly to near-term growth in CO_2 emissions, and total emissions are relatively constant between 2025 and 2075 as forests are exhausted (see Figure 5-14). In the RCW CO_2 emissions are dominated by the growth in fossil-fuel combustion and total emissions increase by a factor of three by 2050. In the Stabilizing Policy scenarios increased end-use efficiency and reforestation contribute significantly to producing decreasing emissions in the near-term, while decreased reliance on fossil fuels in conjunction with continued improvements in efficiency allow for further decreases later on.

TABLE 5-8

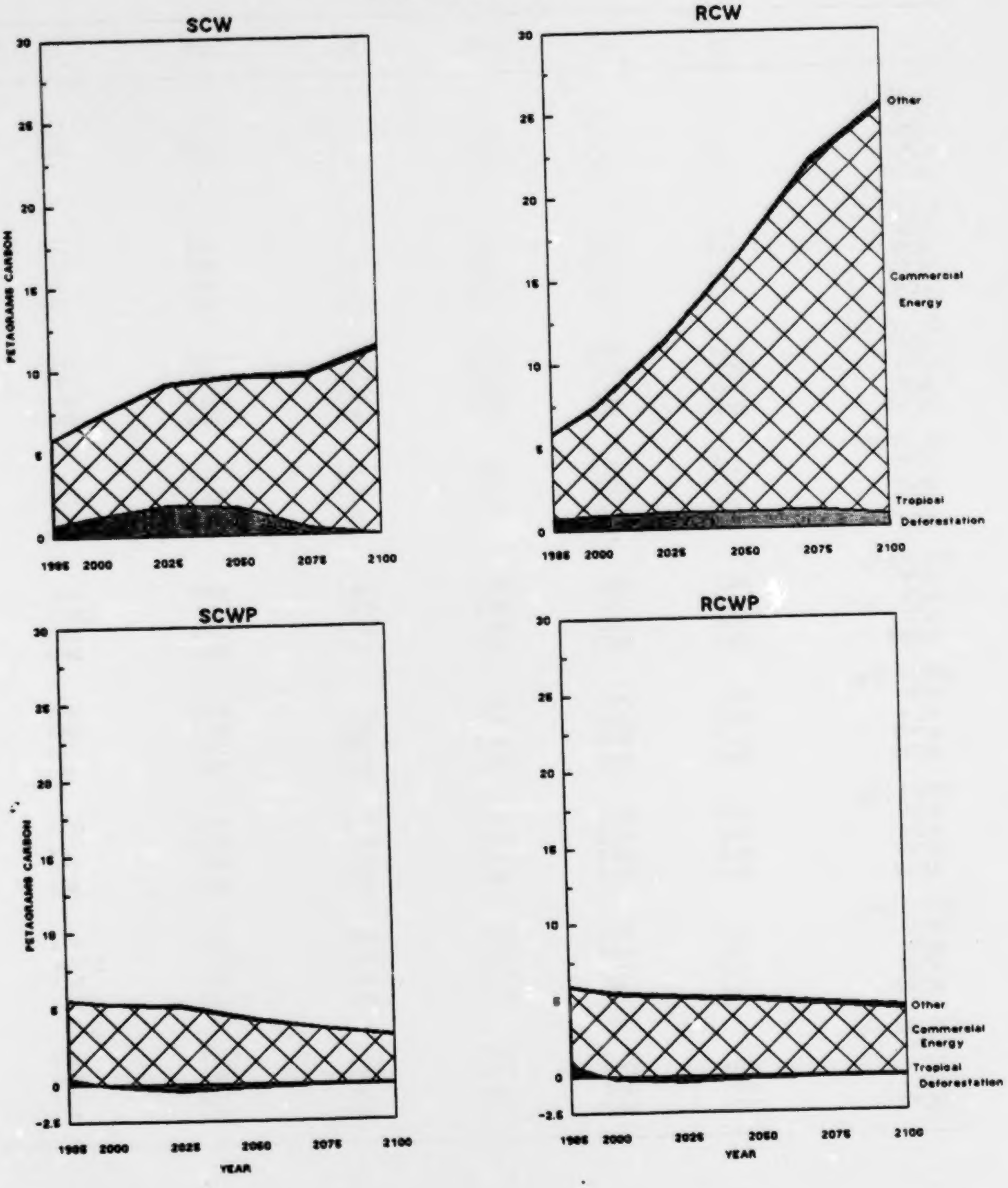
Trace Gas Emissions

	1985	2000	2025	2050	2075	2100
CO_2 (Pg C)						
SCW	5.9	7.2	9.2	9.8	9.7	11.4
RCW	5.9	7.6	11.5	16.6	22.2	25.5
SCWP	5.9	5.3	5.1	4.2	3.7	3.1
RCWP	5.9	5.5	5.2	5.1	4.8	4.5
N_2O (Tg N)						
SCW	11.3	12.3	13.5	13.7	12.2	12.1
RCW	11.3	12.0	13.0	14.0	15.0	15.0
SCWP	11.3	11.0	10.7	10.6	10.6	10.7
RCWP	11.3	11.0	10.8	10.8	10.8	10.9
CH_4 (Tg CH_4)						
SCW	514.4	569.4	676.4	739.9	773.3	815.9
RCW	510.5	576.7	712.4	879.6	1,025.4	1,089.0
SCWP	514.4	519.0	545.0	534.0	522.2	484.7
RCWP	510.5	527.3	558.7	567.2	542.6	508.0
NO_x (Tg N)						
SCW	53.3	59.3	68.8	70.8	65.2	70.1
RCW	53.2	60.0	72.9	91.7	108.2	118.2
SCWP	53.3	50.9	44.8	40.9	41.0	42.6
RCWP	53.2	51.5	50.7	46.1	44.8	43.8
CO (Tg C)						
SCW	502.3	616.1	842.0	858.7	594.7	603.5
RCW	502.0	571.1	699.1	894.6	1,049.9	1,207.1
SCWP	502.3	382.5	286.1	245.5	250.6	250.9
RCWP	502.0	382.3	290.8	241.7	242.0	244.9
CFC-11 (Gg)						
SCW	278.3	292.0	248.1	275.6	280.4	280.8
RCW	278.3	314.2	267.3	300.3	306.3	306.8
SCWP	278.3	261.8	47.3	47.8	50.3	50.6
RCWP	278.3	293.1	60.2	52.4	54.2	54.3
CFC-12 (Gg)						
SCW	363.8	401.1	379.7	404.8	410.3	410.8
RCW	363.8	471.8	437.5	483.6	492.3	493.1
SCWP	363.8	354.2	54.9	62.3	65.7	66.0
RCWP	363.8	433.3	85.9	83.6	86.4	86.6
CFC-22 (Gg)						
SCW	73.8	192.1	385.0	686.5	785.7	794.8
RCW	73.8	247.4	829.1	2,194.2	2,744.9	2,795.6
SCWP	73.8	192.1	385.0	686.5	785.7	794.8
RCWP	73.8	247.4	829.1	2,194.2	2,744.9	2,795.6
CFC-113 (Gg)						
SCW	150.5	119.3	124.2	140.4	140.4	140.4
RCW	150.5	171.8	167.4	190.3	190.3	190.3
SCWP	150.5	93.2	9.0	13.8	13.8	13.8
RCWP	150.5	148.7	19.7	25.4	25.4	25.4

FIGURE 5-14

CO2 EMISSIONS BY TYPE

(Petagrams Carbon)



The regional allocation of CO_2 emissions shows a rapid increase in the share attributed to developing countries in all scenarios (Figure 5-15). This share increases from about 34% currently to 57% by 2025 and levels off at about 60% after 2050 in the RCW. The developing countries account for a little over 50% of CO_2 emissions in the SCW after 2025, with the share from developing countries other than China decreasing after 2050 as deforestation emissions decline. China's share of emissions grows most dramatically in the Stabilizing Policy scenarios as deforestation is eliminated in other developing countries and China becomes by far the world's largest coal consumer. About 70% of global CO_2 emissions are from China and other developing countries by 2100 in the RCWP scenario, but only 42% in the SCWP.

The projected increases in CH_4 emissions in the No Response scenarios are a result of growth in a variety of sources (see Figure 5-16). In the SCW almost 60% of the increase between 1985 and 2050 is due to enteric fermentation and rice cultivation, whereas in the RCW these sources account for less than 40% of the increase and the growth in emissions from fuel production accounts for another 40%. In both of these scenarios emissions from landfills increase steadily, becoming quite significant by the end of the period. Reduced growth in each component is responsible for relatively stable CH_4 emissions in the policy scenarios. The total increases gradually until 2025 and declines after 2050, falling below 1985 levels by the end of the period in both the SCWP and RCWP cases.

The regional contributions to CH_4 emissions do not shift as dramatically as for CO_2 (Figure 5-17). The share of CH_4 emissions from industrialized countries increases in the RCW scenario due to rapid growth in coal production, but this share declines somewhat in the other three scenarios.

Total N_2O emissions do not increase dramatically in any of the scenarios, although we note again that current, and therefore future, emissions of N_2O are highly uncertain. These uncertainties,

FIGURE 5-15

SHARE OF CO2 EMISSIONS BY REGION

(Percent)

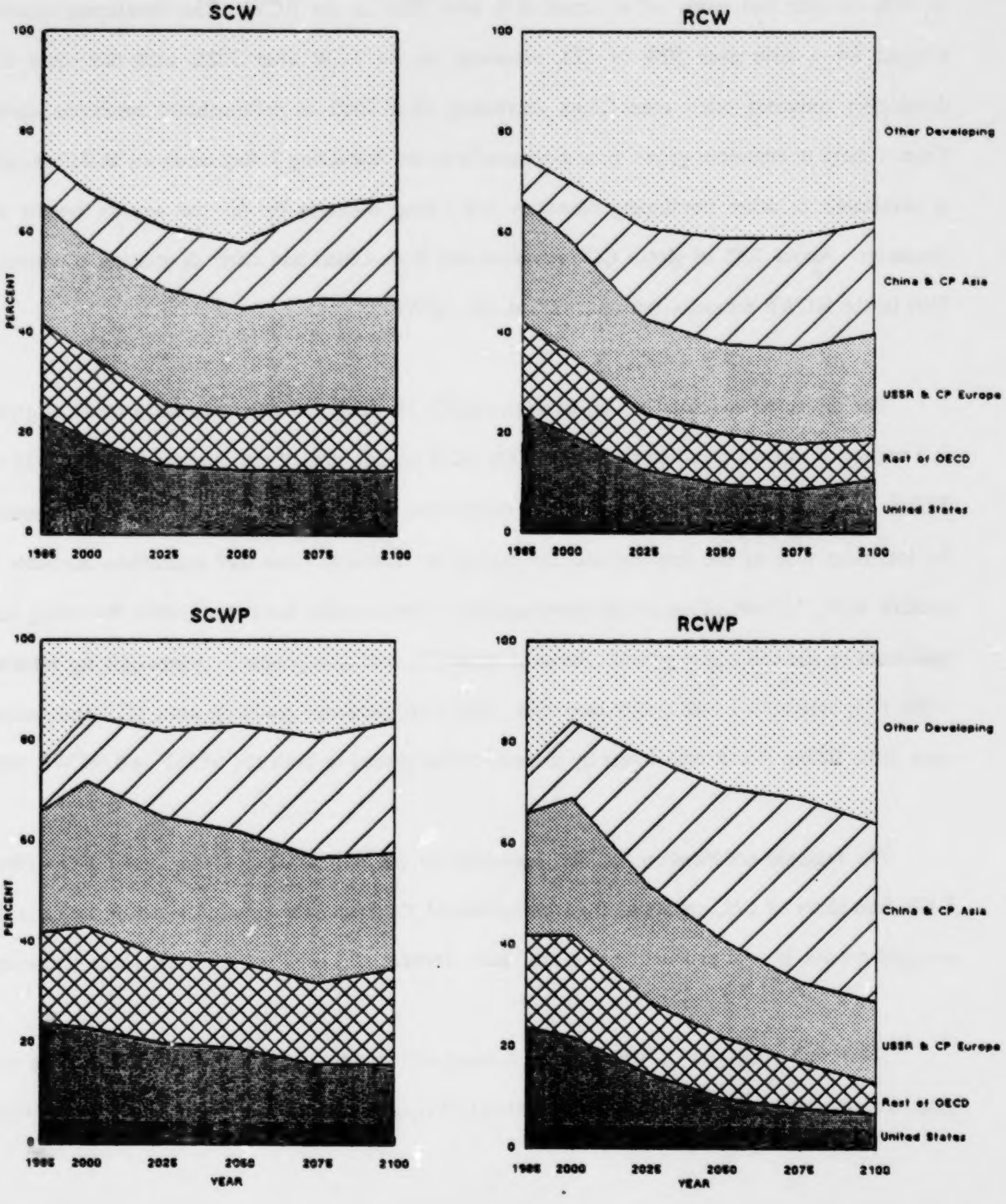


FIGURE 5-16

CH4 EMISSIONS BY TYPE

(Teragrams)

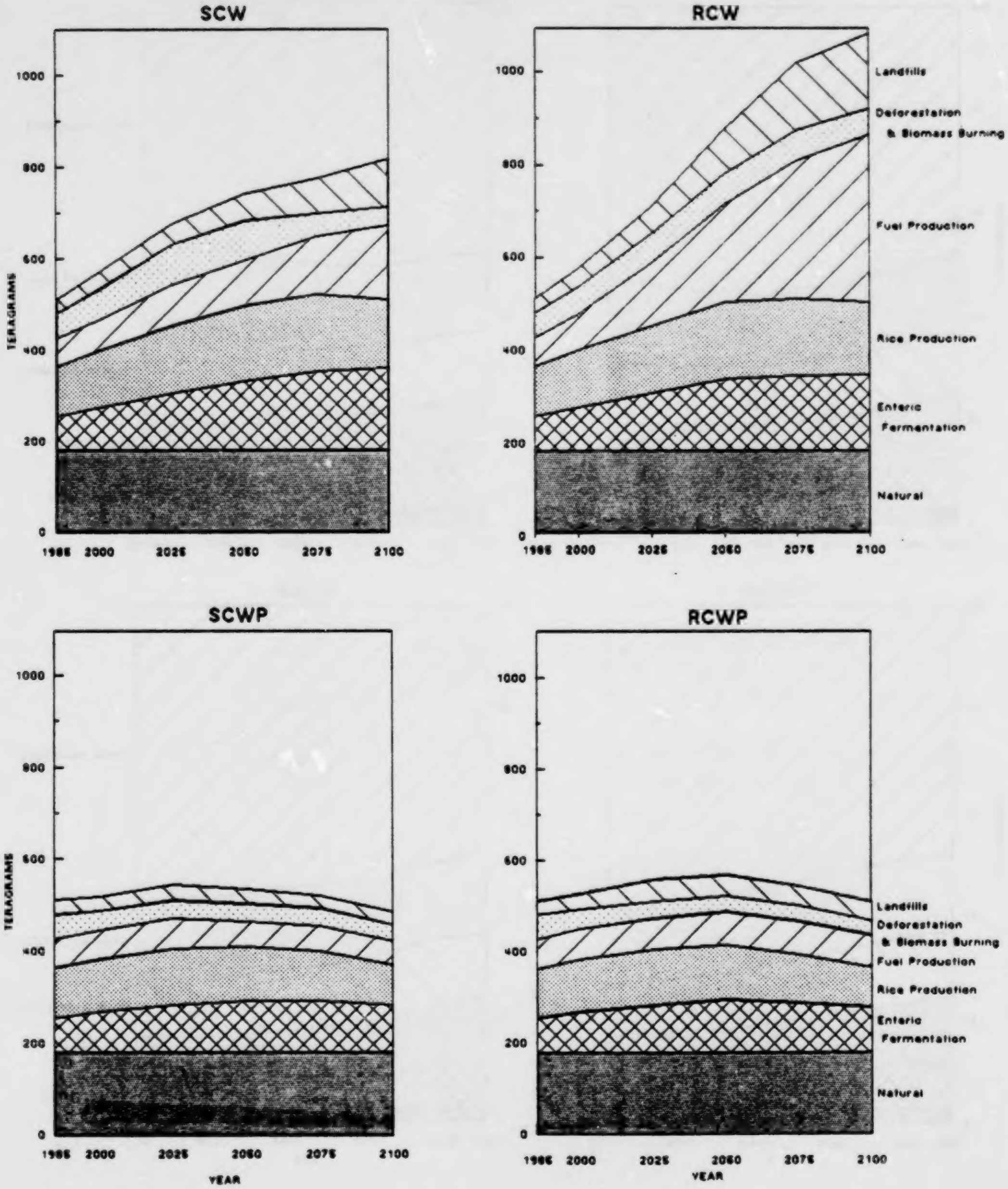
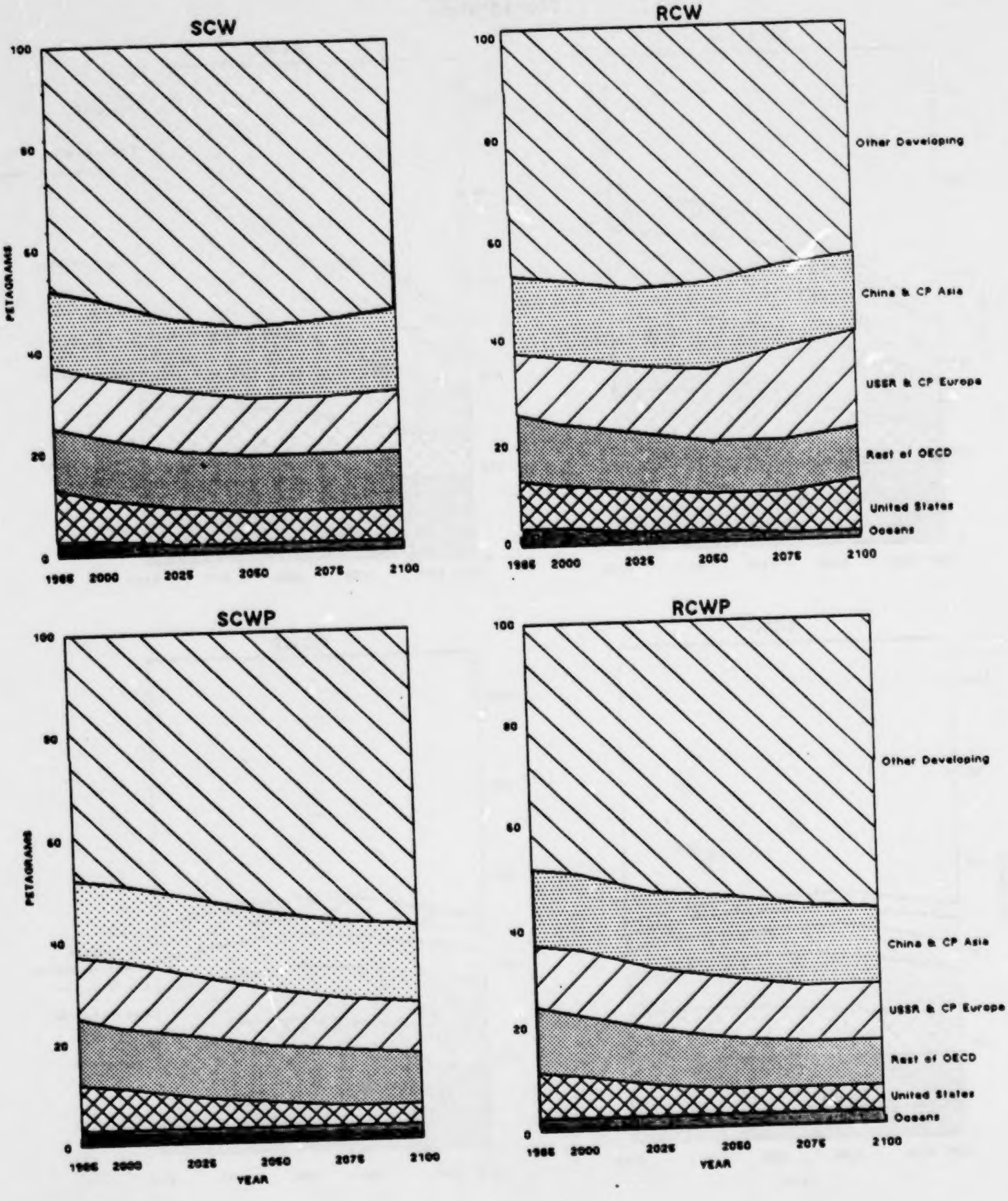


FIGURE 5-17

SHARE OF CH4 EMISSIONS BY REGION
(Petagrams)



however, do not appear to have a large impact on the overall rate or magnitude of climatic change in these scenarios (see Chapter VI). In the SCW, emissions related to deforestation and land-clearing, as well as fertilizer-induced emissions, increase significantly through 2025, and total emissions decline after 2050. In the RCW, emissions growth is driven mainly by a four-fold increase in fossil-fuel combustion emissions between 1985 and 2100. In the policy cases, total emissions decline slightly due to the assumed decreases in emissions per unit of fertilizer use and fossil-fuel combustion, and because deforestation is halted.

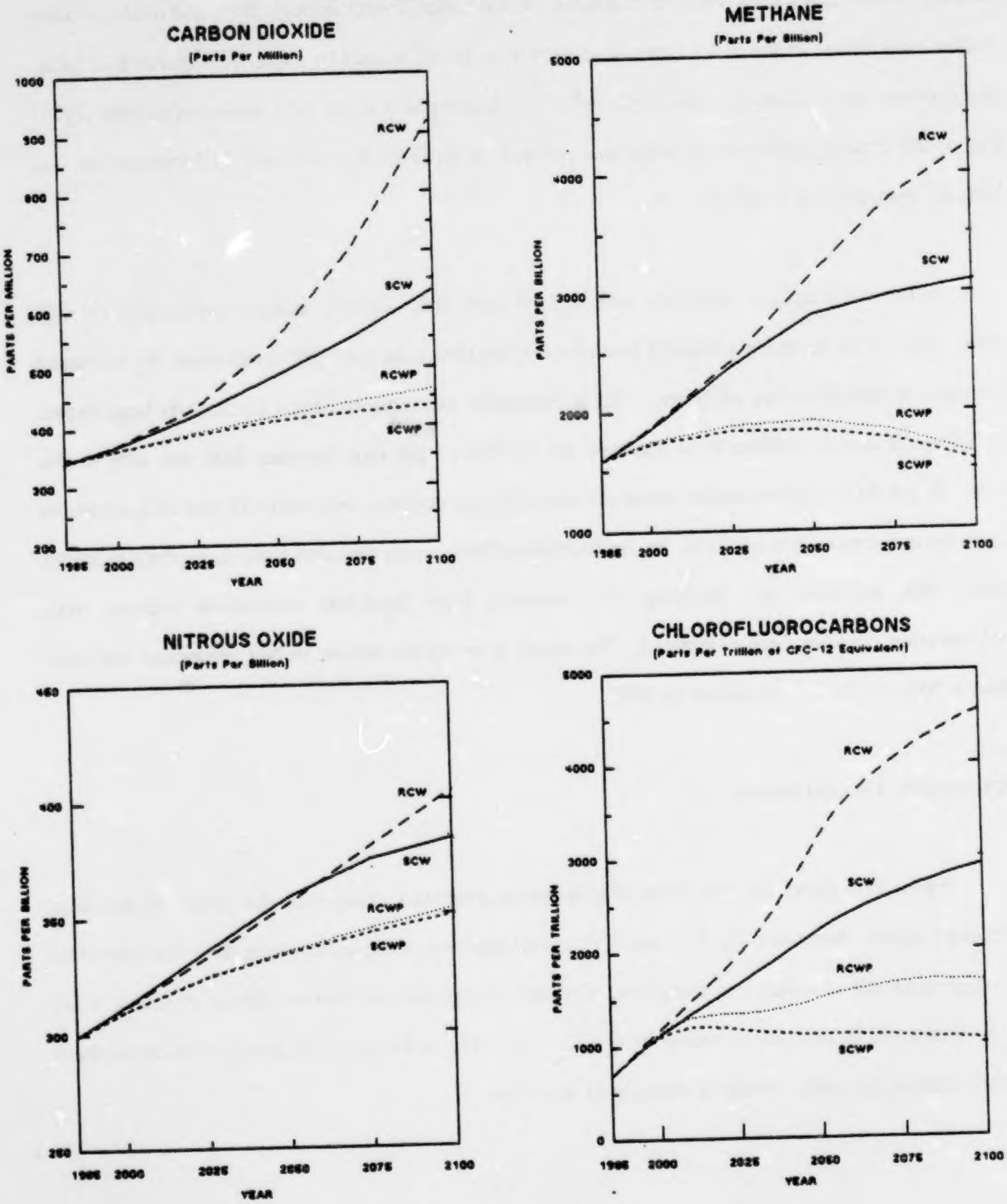
In the No Response scenarios, emissions of both NO_x and CO increase significantly through 2050. After 2050 declining emissions related to deforestation in the SCW compensate for continued increases in energy-related emissions. The deforestation assumptions have a particularly large impact on CO emissions as deforestation accounts for 40-50% of the total between 2000 and 2050 in this case. In the RCW, deforestation emissions are relatively uniform, and both CO and NO_x emissions continue to increase through 2100. In the Stabilizing Policy cases emission controls produce relatively stable NO_x emissions and declining CO emissions from fossil-fuel combustion sources, while deforestation emissions are eliminated. The result is moderate decline in NO_x emissions and more than a 50% cut in CO emissions by 2050.

Atmospheric Concentrations

Figure 5-18 shows concentrations of greenhouse gases that result from the pattern of emissions discussed above. Because CO_2, N_2O, and CFCs are long-lived in the atmosphere, their concentrations respond gradually to changes in emissions. CH_4 has an intermediate lifetime (about 10 years), which is itself affected by changes in emissions of CO, NO_x, CH_4, and other trace gases, so its atmospheric concentration responds rapidly to changes in emissions.

FIGURE 5-18

ATMOSPHERIC CONCENTRATIONS
(3.0 Degree Celsius Climate Sensitivity)



CO_2 concentrations reach twice their preindustrial levels (570 ppm) in about 2080 in the Slowly Changing World scenario; this level is reached by 2055 in the Rapidly Changing World and concentrations more than three times preindustrial values are reached by 2100 (Figure 5-18). Despite declining CO_2 emissions in the policy scenarios, CO_2 concentrations continue to increase throughout the projection period, reaching almost 440 ppm in the SCWP case and 470 ppm in the RCWP case by 2100. It is interesting to note that the fraction of total CO_2 emissions during the 21st Century that remain in the atmosphere in 2100 is 46% in the RCW case and 39% in the RCWP case, so that emission reductions have a more than linear impact on concentrations.

CH_4 concentrations increase by almost a factor of 2 in the SCW and a factor of 2.6 in the RCW, with the most rapid growth occurring between 1985 and 2050 (Figure 5-18). Interestingly, the 2050 concentration obtained in the SCW is similar to the result of linearly extrapolating the currently observed growth rate of 1% per year, whereas the RCW value is close to an exponential extrapolation of current growth; the 2100 values lie substantially below a continuation of such extrapolations for another 50 years. In the policy cases CH_4 concentrations increase by 13-18% between 1985 and 2025, after which they level off and decline to roughly 1985 levels by 2100. CH_4 concentrations are affected by temperature feedbacks on atmospheric chemistry: Increasing the climate sensitivity of the model from 2.0°C to 4.0°C reduces concentrations by 100 ppb in the SCWP and 210 ppb in the RCW.

By contrast with methane, N_2O concentrations increase gradually in all the scenarios as a result of the current imbalance between sources and sinks (Figure 5-18). The concentration increase is about 80 ppb in the SCW and 100 ppb in the RCW compared with 50 ppb in the Stabilizing Policy cases. Thus, the policy assumptions reduce the concentration growth by 40-50%.

CFC concentrations increase dramatically in the No Response scenarios despite the assumption that at least 65% of developing countries and 95% of industrialized countries participate in the Montreal Protocol (Figure 5-18). The total concentration of CFCs weighted by their contribution to the greenhouse effect increases by a factor of 4.2 and 6.5 in the SCW and RCW scenarios, respectively. On the other hand, the phase-out assumed in the policy cases does stabilize CFC concentrations (other than HCFC-22) by 2025, but their total greenhouse forcing still increases by 1.5-2.4 times over current levels.

It is interesting to compare the concentration changes calculated here, on the basis of explicit assumptions linking emissions with activities, to recent studies that have made less formal estimates based primarily on current trends in concentrations and/or emissions (Table 5-9). Our No Response estimates of future concentrations are in good agreement with those of Ramanathan et al. (1985) for 2030 and Dickinson and Cicerone (1986) for 2050. A notable exception is CFCs, for which we expect significantly lower concentrations as a result of the recent Montreal Protocol to control production of these compounds. In addition, our 2030 estimates of N_2O concentrations are somewhat below the lower end of the range given by Ramanathan et al., although they fall within the lower end of Dickinson and Cicerone's range for 2050. The differences between the SCW and RCW scenarios are significantly less than the ranges suggested by these authors for all the compounds listed in Table 5-9--at least partially because the only differences between the SCW and RCW scenarios are assumptions about activity levels and technology, whereas the estimated ranges from the literature also consider uncertainties in current sources, atmospheric chemistry, and ocean carbon uptake (uncertainties in these factors are considered in Chapter VI). Also, the Slowly Changing World and Rapidly Changing World scenarios are not intended to completely bound future possibilities; significant reductions in emissions per unit of GNP are built into the No Response scenarios--if this

TABLE 5-9

Comparison of Estimates of Trace-Gas Concentrations in 2030 and 2050

	Concentrations in 2030							
		GISS						
Trace-Gas	Ramanathan et al. (1985)	A	B	C	SCW	RCW	SCWP	RCWP
CO_2 (ppm)	450	443	427	368	440	450	400	400
CH_4 (ppm)	2.3(1.8-3.3)	3.5	2.5	1.9	2.5	2.6	1.8	1.9
Trop-O_3 (%)	12.5	*	0	0	19	18	-1	-1
N_2O (ppb)	375(350-450)	381	352	314	340	340	330	330
CFC-11 (ppb)	1.1(0.5-2.0)	2.3	0.8	0.2	0.5	0.5	0.3	0.4
CFC-12 (ppb)	1.8(0.9-3.5)	3.9	1.4	0.5	1.0	1.1	0.7	0.8
HCFC-22 (ppb)	0.9(0.4-1.9)				0.4	0.7	0.3	0.6

	Concentrations in 2050							
		GISS						
Trace-Gas	Dickinson & Cicerone (1985)	A	B	C	SCW	RCW	SCWP	RCWP
CO_2 (ppm)	400-600	513	465	368	490	540	410	420
CH_4 (ppm)	2.1-4.0	4.7	2.7	1.9	2.8	3.1	1.8	1.9
Trop-O_3 (%)	15-50	*	0	0	23	26	-2	0
N_2O (ppb)	350-450	480	376	314	360	360	330	340
CFC-11 (ppb)	0.7-3.0	4.2	1.0	0.2	1.2	1.4	0.3	0.3
CFC-12 (ppb)	2.0-4.8	7.3	1.8	0.4	1.2	1.4	0.6	0.7
HCFC-22 (ppb)					0.6	1.7	0.5	1.6

* In this scenario the effect of O_3 and other trace gas changes is approximated by doubling the radiative forcing contributed by CFC-11 and CFC-12.

fails to materialize, and/or if economic growth is more rapid than assumed here, concentrations of a number of greenhouse gases could be significantly higher than is estimated in these scenarios.

Global Temperature Increases

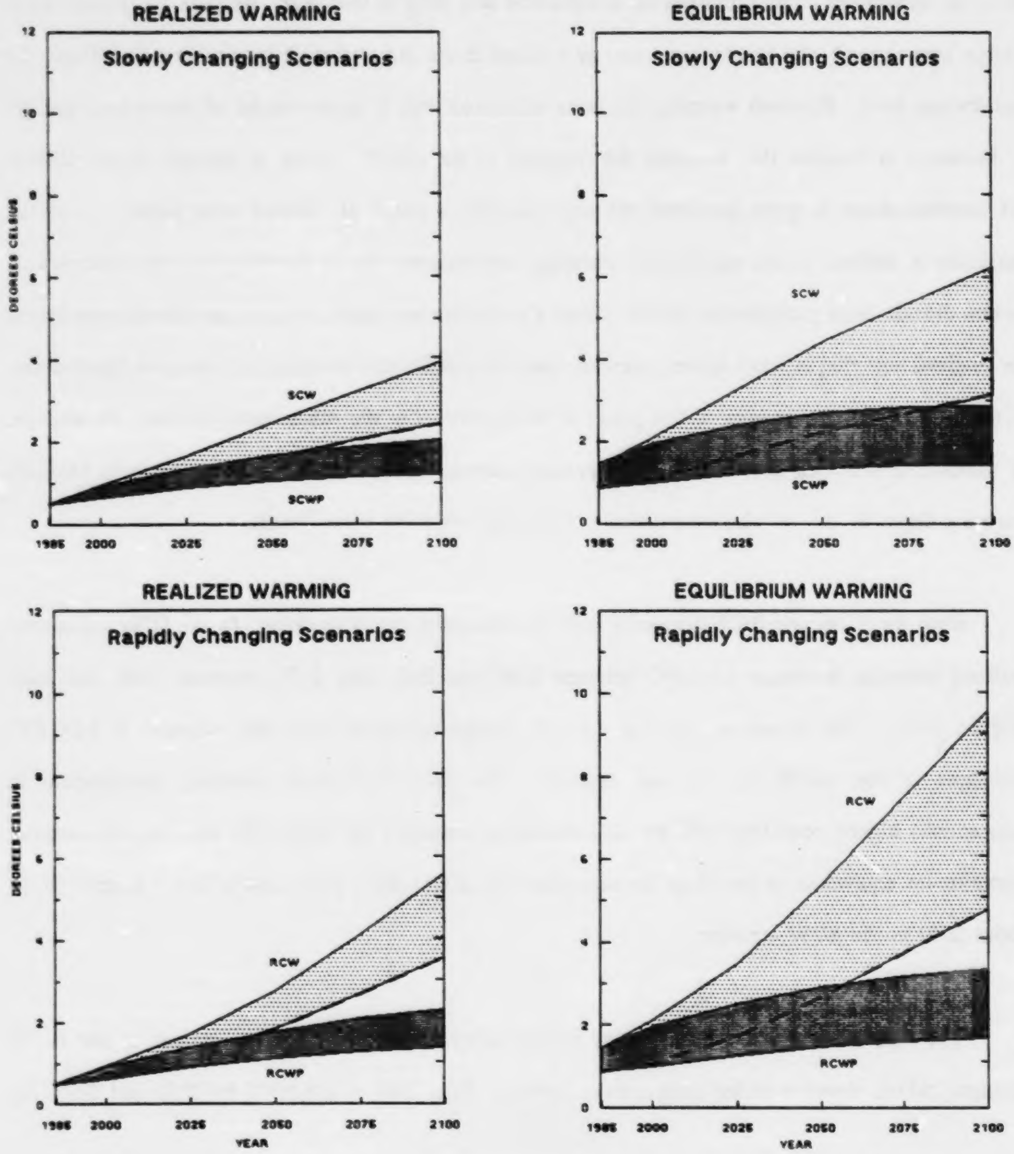
Evaluating the consequences of alternative climate change scenarios is beyond the scope of this report (a variety of potential effects are examined in the companion report *Potential Effects of Global Climate Change on the United States*; Smith and Tirpak, 1988), but an indicator of the relative magnitude of change is needed as a basis for comparing the scenarios considered here. Analysts of trace-gas emissions have often emphasized the date at which carbon dioxide concentrations (or the equivalent combination of trace gases) can be expected to reach twice their pre-industrial level of $2xCO_2$. In the absence of policies to reduce emissions, however, climate change is potentially open-ended. Atmospheric composition and climate would continue to change after the $2xCO_2$ level were reached and the ecological and social consequences may depend as much on what happens after CO_2 doubles (if it does) as on when this benchmark occurs. More relevant to ecological and social systems are the average and maximum rate of climatic change. In order to compare scenarios, we therefore focus on the average rate at which global temperature may increase during the next century as well as the maximum rate of change. We emphasize that these parameters are only indicators of global change; changes at the regional level will vary in both magnitude and timing and changes in precipitation may be as important as changes in temperature. Nonetheless, the global quantities calculated here can be used to compare the scenarios presented here among themselves and with results of more detailed climate models.

The changes in concentrations shown in Figure 5-18 produce the estimated global temperature changes shown in Figure 5-19 for a range of climate sensitivity (2.0-4.0°C equilibrium increase in

FIGURE 5-19

REALIZED AND EQUILIBRIUM WARMING

(Degrees Celsius; 2.0 - 4.0 Degree Climate Sensitivity)



REALIZED WARMING — Slowly Changing Scenarios

EQUILIBRIUM WARMING — Slowly Changing Scenarios

REALIZED WARMING — Rapidly Changing Scenarios

EQUILIBRIUM WARMING — Rapidly Changing Scenarios global temperature from doubling the atmospheric concentration of CO_2; see Chapter III). Both the "equilibrium warming commitment" and the "realized warming" are presented as a function of time. The equilibrium warming commitment for any given year is the temperature increase that would occur in equilibrium if the atmospheric composition was fixed in that year. Because the oceans have a large heat capacity the temperature change realized in the atmosphere lags considerably behind the equilibrium level. Realized warming has been estimated with a simple model of ocean heat uptake as discussed in Chapter III. Because the response of the climate system to changes in greenhouse gas concentrations is quite uncertain we also consider a range of "climate sensitivities". Climate sensitivity is defined as the equilibrium warming commitment due to doubling the concentration of carbon dioxide from preindustrial levels. Given a particular emissions scenario and climate sensitivity, the realized warming is much more uncertain than the equilibrium warming commitment because the effective heat storage capacity of the ocean is not known. On the other hand, because the amount of unrealized warming increases with increasing climate sensitivity, for a given scenario realized warming depends less on climate sensitivity than does warming commitment.

Both the SCW and RCW scenarios lead to substantial global warming. In the SCW, estimated realized warming increases 1.0-1.5°C between 2000 and 2050, and 2-3°C between 2000 and 2100 (Figure 5-19). The maximum decadal rate of change associated with this scenario is 0.2-0.3°C sometime in the middle of the next century. The total equilibrium warming commitment is substantially higher, reaching 3-6°C by 2100 relative to preindustrial levels. The equilibrium warming commitment equivalent to doubling the concentration of CO_2 from preindustrial levels is reached by about 2040 in the SCW scenario.

The rate of change during the next century would be more than 50% greater in the RCW scenario, which shows a global temperature increase from 2000 of 1.2-1.9°C by 2050 and 3-5°C by

2100 (Figure 5-19). In this case the maximum rate of change is 0.4-0.6°C per decade, which occurs sometime between 2070 and 2100. The equilibrium warming commitment is 5-10°C by 2100 in this scenario and the $2xCO_2$ equivalent level is reached by about 2030.[11]

By contrast, the rate of climatic change in the Stabilizing Policy scenarios would be less than 1.6°C per century. Global temperatures in the SCWP case increase by 0.4-0.8°C from 2000 to 2050 and 0.6-1.1°C from 2000 to 2100; corresponding values are 0.5-0.9°C and 0.8-1.4°C in the RCWP case. The maximum rate of change in these scenarios is less than 0.3°C per decade and occurs before 2010, largely as a result of warming to which the world may already be committed. (Indeed, the 0.3°C per decade figure, obtained assuming a climate sensitivity of 4°C, occurs at the very beginning of the simulation and may be an artifact of how the model is initialized.) In these cases the additional commitment to warming is greater between 2000 and 2050 than it is between 2050 and 2100: 0.3-0.9°C versus 0.1-0.4°C. Total equilibrium warming commitment reaches 1.4-2.8°C in the SCWP and 1.7-3.3°C in the RCWP. While not without some risk, the rate of change represented by the Stabilizing Policy scenarios would give societies and ecosystems much more time to adapt to climatic change than would be the case in the No Response scenarios.

Carbon dioxide accounts for more than 65% of increased commitments to global warming between 2000 and 2100 in all of the scenarios analyzed in this report (Figure 5-20). This represents a significantly higher estimate of the role of CO_2 compared to roughly 50% in the last few decades and in Ramanathan et al.'s scenario for 2030. Much of this difference is due to smaller increases in CFCs in our scenarios due to our assumption that the Montreal Protocol comes into force. In addition, growth in emissions of CH_4 and N_2O is projected to be slower than that of CO_2, particularly

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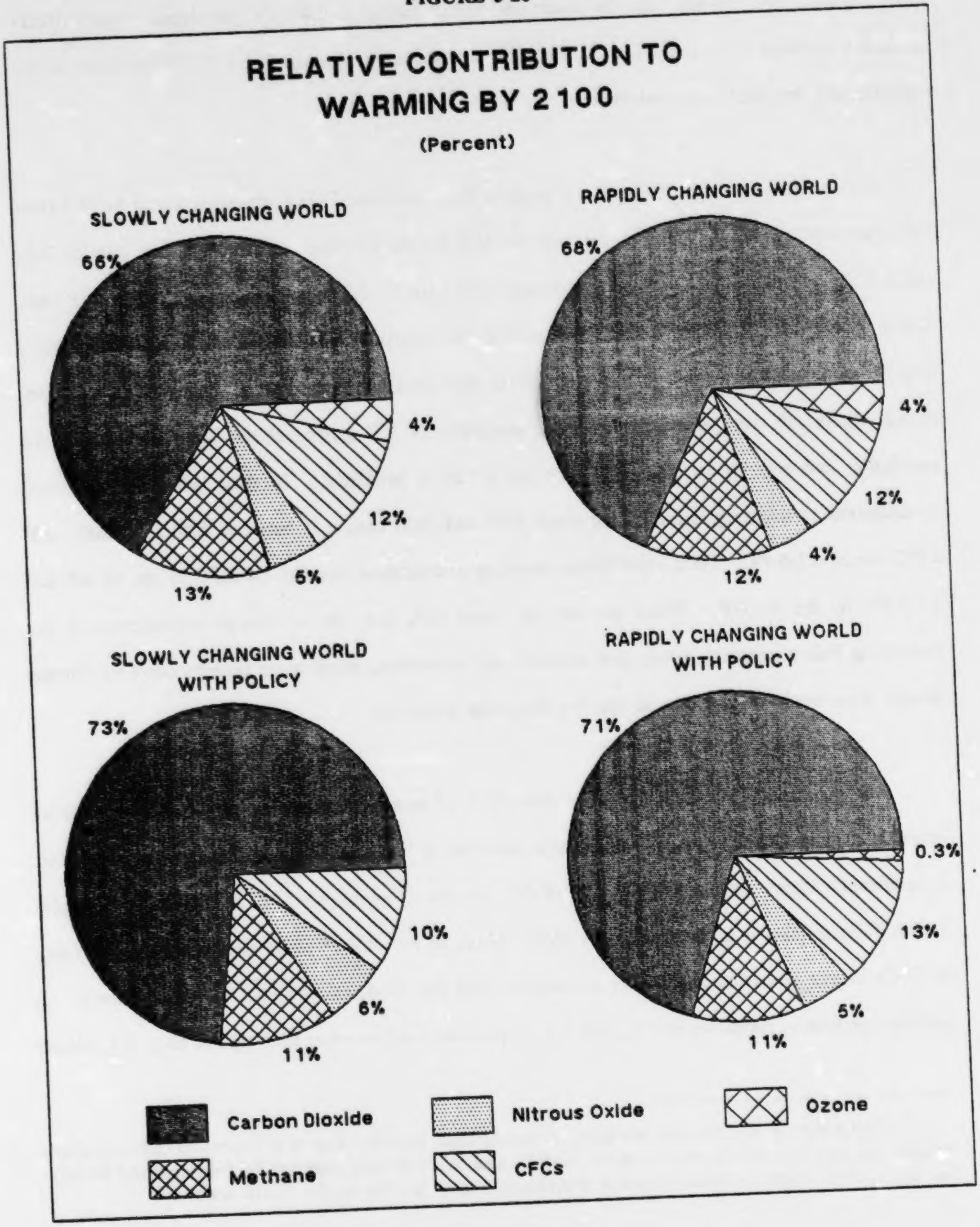
[11] Estimates of equilibrium warming commitments greater than 6°C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

FIGURE 5-20


RELATIVE CONTRIBUTION TO WARMING BY 2100
(Percent)
SLOWLY CHANGING WORLD
66%
4%
12%
5%
13%
RAPIDLY CHANGING WORLD
68%
4%
12%
4%
12%
SLOWLY CHANGING WORLD WITH POLICY
73%
10%
6%
11%
RAPIDLY CHANGING WORLD WITH POLICY
71%
0.3%
13%
5%
11%
Carbon Dioxide
Nitrous Oxide
Ozone
Methane
CFCs

after 2030. The role of CO_2 is greatest in the policy scenarios because our assumptions lead to relatively stable concentrations of CH_4 and tropospheric ozone, while CO_2 concentrations continue to increase gradually.

Comparison with General Circulation Model Results

Hansen et al. (1988) analyzed three transient trace-gas scenarios using the GISS GCM. The GISS A scenario, based on exponentially extrapolating current greenhouse gas trends, most closely resembles our RCW with 4.0°C climate sensitivity (the climate sensitivity of the GISS GCM is 4.2°C). Indeed, both the equilibrium and realized global warming in these cases are within 0.1°C in 2025.[12] By 2050 the continuation of exponential growth in trace-gas concentrations in the GISS A scenario leads to an equilibrium warming commitment that is about 40% higher than in the RCW, with a corresponding realized warming of 3.4 versus 2.8°C (all references to realized warming in the GISS scenarios are based on 5-year running means, Figure 3b in Hansen et al., 1988a). By 2060, the end of the GISS simulation, the realized warming in the GISS A scenario is 4.2°C compared with 3.3°C in the RCW. The GISS B scenario, which is based on linearly increasing trace-gas concentrations at current rates, is most similar to the RCWP case (with 4.0°C climate sensitivity). These two cases have very similar equilibrium warming commitment and realized warming in 2030 (the end of the GISS simulation for this scenario). The final scenario examined by GISS (case C) assumes that atmospheric composition is stable after 2000, which leads to realized warming of about 0.9°C by 2040. The policy cases examined here do not achieve this result; realized warming reaches 1.3-1.4°C by 2025 if the climate sensitivity is 4.0°C. Thus, the GISS scenarios bracket the range of the scenarios developed here, and may provide some indication of the regional differences in the rates and magnitude of change that might be associated with our cases.

---

[12] The path to 2025, however, is not identical. The GISS scenarios are referenced to the atmospheric composition of 1960, whereas our scenarios are referenced to the estimated preindustrial atmospheric composition. Thus, the warming commitment in 2000 is already 2.1°C in the RCW, whereas it is only 1.9°C in the GISS A scenario.

Relative Effectiveness of Selected Strategies

The major assumptions that distinguish the Worlds where governments provide leadership in pursuing stabilizing policies from the Worlds with no such policies have been grouped into eleven categories in order to examine the relative importance of different policy strategies. Each set of options was applied individually to the RCW case; the combination of all the strategies represents the RCWP case. Figure 5-21 presents the results in terms of the effect of each policy strategy in reducing the equilibrium warming commitment in 2050 and 2100. This analysis suggests that accelerated energy efficiency improvements, reforestation, modernization of biomass use, and carbon emissions fees could have the largest near-term impact on the rate of climatic change. In the long run, advances in solar technology and biomass plantations also play an essential role.

CONCLUSIONS

While the future will never be anticipated with certainty, it is useful to explore the consequences of alternative plausible scenarios. The results of this exercise suggest that even with sluggish rates of economic growth and optimistic assumptions regarding technical innovation, the world could experience significant rates of climatic change during the next century. Temperature increases reach 3-4°C by 2100 under our assumptions; and the world would be committed to an additional warming of up to 2°C at this date. With higher rates of economic growth, certainly the goal of most governments, significantly more rapid rates of climatic change are possible. With our assumptions, which involve lower global energy use than considered in many previous studies, a

FIGURE 5-21

STABILIZING POLICY STRATEGIES: DECREASE IN EQUILIBRIUM WARMING COMMITMENT

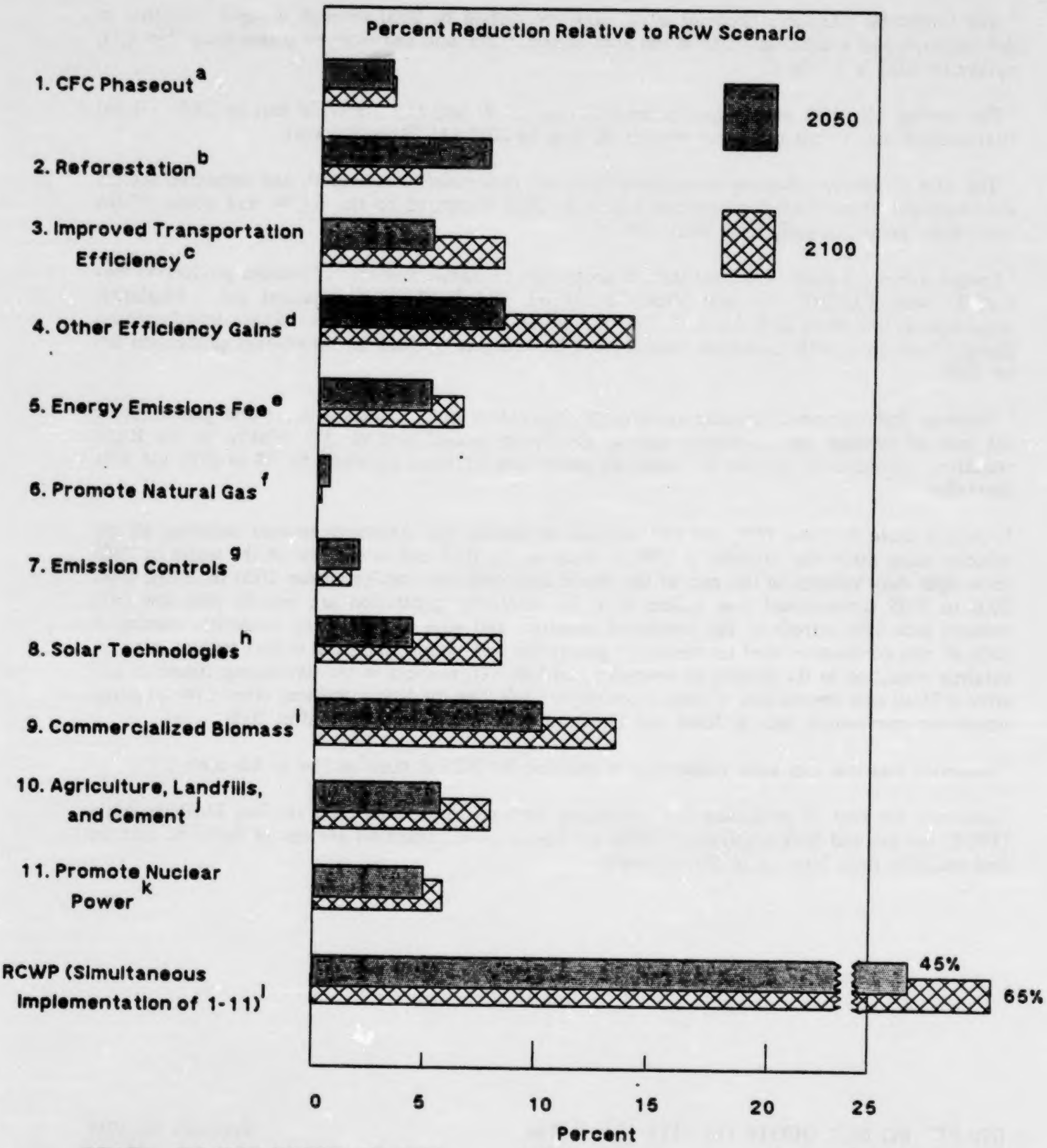


FIGURE 5-21 -- NOTES

Impact Of Stabilizing Policies On Global Warming

[a] A 100% phaseout of CFCs by 2003 and a freeze on methyl chloroform is imposed. There is 100% participation by industrialized countries and 94% participation in developing countries.

[b] The terrestrial biosphere becomes a net sink for carbon by 2000 through a rapid reduction in deforestation and a linear increase in the area of reforested land and biomass plantations. Net CO_2 uptake by 2025 is 0.7 Pg C.

[c] The average efficiency of new cars in the U.S. reaches 40 mpg (5.9 liters/100 km) by 2000. Global fleet-average automobile efficiency reaches 50 mpg by 2025 (4.7 liters/100 km).

[d] The rate of energy efficiency improvements in the residential, commercial, and industrial sectors are increased about 0.1-0.2 percentage points by 2025 compared to the RCW, and about 0.3-0.4 percentage points annually from 2025-2100.

[e] Emission fees are placed on fossil fuels in proportion to carbon content. Maximum production fees (1985$) were $0.50/GJ for coal $0.36/GJ for oil, and $0.23/GJ for natural gas. Maximum consumption fees were 28% for coal, 20% for oil, and 13% for natural gas. These fees increased linearly from zero, with maximum consumption fee changed by 2025 and maximum production fee by 2050.

[f] Assumes that economic incentives accelerate exploration and production of natural gas, reducing the cost of locating and producing natural gas by an annual rate of .5% relative to the RCW scenario. Incentives for gas use for electricity generation increases gas share by 5% in 2025 and 10% thereafter.

[g] Assume more stringent NO_x and CO controls on mobile and stationary sources including all gas vehicles using three-way catalysts in OECD countries by 2000 and in the rest of the world by 2025 (new light duty vehicles in the rest of the world uses oxidation catalysts from 2000 to 2025); from 2000 to 2025 conventional coal boilers used for electricity generation are retrofit with low NO_x burners with 85% retrofit in the developed countries and 40% in developing countries; starting in 2000 all new combustors used for electricity generation and all new industrial boilers require selective catalytic reduction in the developed countries and low NO_x burners in the developing countries and after 2025 all new combustors of these types require selective catalytic reduction; other new industrial non-boiler combustors such as Kilns and Dryers require low NO_x burners after 2000.

[h] Assumes that low cost solar technology is available by 2025 at costs as low as 4.6 cents/kwh.

[i] Assumes the cost of producing and converting biomass to modern fuels reaches $4.00/gigajoule (1985$) for gas and $6.00/gigajoule (1985$) for liquids. The maximum amount of liquid or gaseous fuel available from biomass is 210 exajoules.

FIGURE 5-21 -- NOTES (continued)

Impact Of Stabilizing Policies On Global Warming

[j] Assumes that research and improved agricultural practices result in an annual decline of 0.5% in the emissions from rice production, enteric fermentation, and fertilizer use. CH_4 emissions from landfills assumed to decline at an annual rate of 2% in developed countries due to policies aimed at reducing waste and landfill gas recovery, emissions in developing countries continue to grow until 2025 then remain flat due to incorporation of the source policies. Technological improvements reduce demand for cement by 25%.

[k] Assumes that technological improvements in nuclear design reduce cost by about $4/gigajoule (1985$) by 2050 (about 0.5% per year efficiency improvement).

[l] Impact on warming when all the above measures are implemented simultaneously. The sum of each individual reduction in warming is not precisely equal to the difference between the RCW and RCWP cases because not all the strategies are strictly additive.

warming of 4-6°C could be expected by 2100, with an additional commitment of 1-4°C by that date. On the other hand, by vigorously pursuing a variety of technical and policy options simultaneously, it would be possible to reduce the average rate of warming during the next century by more than 60%. Chapters VII-IX of this report explore these options in more detail.

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CHAPTER VI

SENSITIVITY ANALYSES

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FINDINGS

- The degree of participation by developing countries in policies to limit warming is one of the most important factors affecting equilibrium temperatures in the year 2100. If only industrialized countries adopt policy measures, equilibrium temperatures could increase by 40% or more relative to scenarios with global cooperation. This suggests that, despite uncertainties about future economic growth rates, developing countries will be a significant determinant in the ultimate level of global warming.

- Delaying any response to global warming by OECD and East Bloc Countries until the year 2010 and by developing countries until 2025 might increase the equilibrium warming commitment in 2050 by 30-40%.

- The sensitivity of the climate system to a given increase in greenhouse gases is among the most important causes for uncertainty about the ultimate magnitude of global warming. For most of the analysis in this report, we have assumed that the climate sensitivity to doubling CO_2 is 2.0 to 4.0°C; broadening the range of climate sensitivity to between 1.5 and 5.5°C for a CO_2 doubling causes the estimated range for equilibrium warming in 2050 to become 2.0-7.4°C in the Rapidly Changing World scenario. The impact on realized warming is less: the estimated range for 2050 increases from 1.9-2.8°C to 1.5-3.2°C. This uncertainty has important implications for the timing and stringency of policy responses. Even the lower values, when considered with information on the impacts of global warming, suggests a need for caution about future emissions.

- Uncertainties in biogeochemical feedbacks appear to be the potentially most important reason to suspect that global warming may ultimately be greater than predicted by current general circulation models. Changes in the ocean circulation, methane releases from hydrates, bogs, and rice cultivation and other positive feedbacks could amplify realized warming in 2100 by 20-40% for a climate sensitivity of 2.0-4.0°C. These estimates are speculative, they are based on the fragmentary evidence currently available, and these positive feedbacks may not occur or may be delayed until the later part of the next century, but the potentially large impact on the magnitude of warming suggests that even more drastic policy measures than those considered in the Rapidly Changing World with Stabilizing Policies scenario might be needed.

- Sensitivity analyses with four ocean models for CO_2 uptake suggest that the path of atmospheric concentrations could follow somewhat different trajectories, but very little difference is observed in equilibrium warming for the year 2100. These equilibrium temperatures differ by at most 10% depending on the type of ocean model. More complex ocean circulation models currently in the research stage could broaden or decrease this range in the future.

- Assumptions about the total supply of oil and gas are among the least significant factors affecting global warming in the year 2100. While gas may be desirable as a transition fuel, sensitivity tests that assume very optimistic estimates of oil and gas availability at each price level suggest only small changes in global warming. A larger impact could occur if policy measures were adopted to take advantage of the assumed increases in gas resources.

- The sources of methane are subject to considerable uncertainty. Estimates of some individual emission sources vary by a factor of two to three. Sensitivity tests that consider extreme assumptions about anthropogenic methane emission sources suggest that uncertainties in this budget could cause equilibrium warming commitments in 2100 to vary by about 5%. These results should not be interpreted to mean that methane is not an important greenhouse gas, but simply that uncertainties in the current budget do not greatly affect the ultimate temperatures derived in this report.

- A comparison between current atmospheric concentrations and growth rates for the greenhouse gases and those calculated with the atmospheric composition model, based on estimates of preindustrial concentrations and past emissions, show good agreement. The largest discrepancies are for relatively short-lived gases that have been increasing rapidly in recent years, such as HCFC-22 and carbon tetrachloride.

- Non-greenhouse gases such as NO_x, CO, and Non-methane hydrocarbons (NMHC) affect the lifetimes and concentrations of tropospheric ozone and methane. A comparison of different chemistry models suggests that increases in methane concentrations may vary by approximately a factor of two for similar assumptions about NO_x/CO/NMHC. This range may be attributed to differences in initial budgets and modeling approaches and may ultimately increase or decrease as other models become available.

- The most important determinant of future atmospheric concentrations of methane appears to be the growth rate of methane sources. While NO_x and

CO affect the lifetime of methane, model studies suggest that assumptions about the emissions of these gases are less important than assumptions about the direct emissions of methane. However, considerable research is needed to further our understanding of the chemistry of the atmosphere.

- There is considerable uncertainty about future concentrations of tropospheric ozone and about changes in composition at different altitudes. While model comparisons all suggest that increases in ozone are likely, the effect of these changes in global temperatures is difficult to predict.

- For the major sensitivity analyses presented in this chapter, Table 6-1 summarizes the impact on realized warming and equilibrium warming by 2050 and 2100 (assuming a 3.0°C climate sensitivity). Throughout this chapter results are discussed for 2.0-4.0°C climate sensitivities for the Rapidly Changing World Scenario, with any figures using the midpoint of this range, i.e., a 3.0°C climate sensitivity, unless stated otherwise. Other assumptions would not change the basic findings, only the absolute size of the impacts; these are presented in Appendix C.

TABLE 6-1

Impact of Sensitivity Analyses on Realized Warming and Equilibrium Warming
(degrees Celsius--3.0°C climate sensitivity)

	2050		2100	
	Realized	Equilibrium	Realized	Equilibrium
Rapidly Changing World - No Response (RCW)	2.4°	4.0°	4.7°	7.2°*
Rapid Changing World - Stabilizing Policies (RCWP)	1.5	2.2	1.9	2.5
Sensitivity Case Assumptions				
No Participation by Developing Countries[a]	2.0-2.1	3.1-3.3	3.2-3.7	4.6-5.6
Global Delay in Adopting Policies[b]	2.0	3.1	2.6	3.5
Non-Fossil Technology[c]	2.1-2.3	3.4-3.7	3.6-4.0	5.3-5.9
Fossil Resources				
High Coal Prices[d]	2.1	3.5	3.6	5.3
High Oil Supply[e]	2.4	4.0	4.7	7.1*
High Gas Supply[f]	2.4	4.0	4.7	7.2*
Methane Budget[g]	2.3-2.5	3.9-4.2	4.6-5.0	7.0-7.6*
High CO Emissions		To be added		
N_2O From Fertilizer				
Anhydrous Ammonia[h]	2.4	4.0	4.7	7.2*
N_2O Leaching[i]	2.4	4.0	4.7	7.2*
N_2O From Combustion[j]	2.4	4.0	4.7	7.2*

* Estimates of equilibrium warming commitment greater than 6°C represent extrapolations beyond the range tested in most climate models; this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

TABLE 6-1 (continued)

Impact of Sensitivity Analyses on Realized Warming and Equilibrium Warming

(degrees Celsius--3.0°C climate sensitivity)

	2050		2100	
	Realized	Equilibrium	Realized	Equilibrium
CO_2 From Biomass[k]	2.4	4.1	4.8	7.3*
CO_2 Models[l]				
Oeschger et al.[m]	-	3.9	-	6.9
Bolin et al.[n]	-	3.9	-	6.9
Bjorkstrom[o]	-	3.9	-	6.9
Siegenthaler[p]	-	3.9	-	6.3
Unknown Sink[q]	2.2-2.5	3.7-4.2	4.1-4.9	6.2-7.4*
1.5-5.5°C Sensitivity[r]	1.5-3.2	2.0-7.4	2.9-6.6	3.6-13.2*
Heat Diffusion[s]	1.9-2.7	4.0	3.9-5.3	7.2*
Prather Model				
CFC-11 Lifetime[t]	2.4	4.0	4.7	7.2*
Chlorine/Col O_3[u]	2.3	3.8	4.4	6.6
Trop O_3/CH_4[v]	2.4	4.1	4.8	7.3*
OH/NO_x[w]	2.4	4.0-4.1	4.7-4.8	7.1-7.3*
Feedbacks				
Ocean Circulation[x]	3.1	4.1	7.1*	7.6*
Methane[y]	2.7	4.6	5.5	8.4*
CO_2/CH_4/Uptake[z]	3.0	4.9	6.3	8.9*

* Estimates of equilibrium warming commitments greater than 6°C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

TABLE 6-1 -- NOTES

[a] Developing countries were assumed to not participate in climate stabilization policies. The range represents uncertainty in the rate of technological diffusion, i.e., even if developing countries do not participate, they will indirectly benefit from technological improvements as a result of stabilization policies among the developed countries.

[b] Impact if developed countries do not respond to global warming until 2010; developing countries delay to 2025.

[c] These ranges represent modest to optimistic assumptions about future commercial availability of non-fossil technologies, e.g., solar photovoltaics, advanced nuclear power designs, and synthetic fuel production from biomass. Solar photovoltaic costs decline to 4.6 cents/kwh (1985$) by 2020 in the optimistic scenario and by 2050 in the modest assumptions. Nuclear costs decline 0.5% annually with the optimistic assumptions and remain relatively flat in the modest assumptions. The cost of producing and converting biomass to modern fuels reaches $4.00/gigajoule for gas and $6.00 (gigajoule) for liquids by 2020 in the optimistic assumptions and by 2050 in the modest assumptions. The total amount of fuel available from biomass is 210 EJ.

[d] The impact of an escalation in coal prices above the RCW case by about 1% annually from 1985 to 2100.

[e] The impact of an increase in global oil resources to 25,000 EJ, more than double the estimate in the RCW case, assuming proportionate increases in resource availability at each cost level.

[f] The impact of an increase in global natural gas resources to 27,000 EJ, more than 2.5 times the estimate in the RCW case, assuming proportionate increases in resource availability at each cost level.

[g] These ranges represent assumptions about the relative sizes of anthropogenic versus non-anthropogenic sources of methane emissions, thereby affecting growth in emissions over time, i.e., high emission levels (373 Tg CH_4) from anthropogenic activities such as fuel production and landfilling with low emission levels (137 Tg CH_4) from natural processes such as oceans and wetlands, versus low anthropogenic emissions (245 Tg CH_4) with high natural emissions (265 Tg CH_4).

[h] The impact of elevating the emission coefficient for the anhydrous ammonia fertilizer type (the percent of N evolved as N_2O) from 0.5% to 2.0%.

[i] The impact of assuming additional N_2O emissions from fertilizer leaching into surface water and ground water, modeled by increasing all the fertilizer emission coefficients by 1 percentage point.

[j] The impact of higher emission coefficients for N_2O from combustion; assumes that N_2O emissions are about 25% of NO_x emissions and the N_2O emissions from combustion sources in 1985 equaled 2.3 Tg N, over 2 times the level assumed in the RCW case.

[k] The impact of assuming a higher estimate for the amount of carbon initially contained in forest vegetation and soils (roughly a 50-100% increase) and a more rapid rate of change in land-use, resulting in emissions of carbon of 281 Pg from 1980 and 2100 compared to 188 Pg C in the RCW scenario.

TABLE 6-1 -- NOTES (continued)

[l] Realized warming was not calculated in these tests.

[m] This box-diffusion model represents carbon turnover below 75 meters as a purely diffusive process.

[n] This is a 12-compartment regional model which divides the Atlantic and Pacific-Indian Oceans into surface-, intermediate-, deep-, and bottom-water compartments and divides the Arctic and Antarctic Oceans into surface- and deep-water compartments.

[o] This is an advective-diffusive model which divides the ocean into cold and warm compartments; water downwells directly from the cold surface compartment into intermediate and deep layers.

[p] An outcrop-diffusion model that allows direct ventilation of the intermediate and deep oceans in high latitudes by incorporating an outcrop connecting all sublayers to the atmosphere.

[q] These ranges represent the impact of alternative assumptions about the "unknown carbon sink" that absorbs the unaccounted-for carbon in the carbon cycle. Two sensitivities were analyzed: 1) a high case, where the size of the unknown sink increases at the same rate as atmospheric CO_2 levels compared with preindustrial levels; and 2) a low case, where the size decreases to zero exponentially at 2% per year.

[r] Atmospheric response to a doubling of CO_2 was varied from 1.5-5.5°C.

[s] Heat diffusion in the oceans is modeled as a purely diffusive process. To capture some of the uncertainty regarding actual heat uptake, the base case eddy-diffusion coefficient of 0.55×10^{-4} m^2/sec was increased to 2×10^{-4} and decreased to 2×10^{-5} m^2/sec.

[t] The atmospheric lifetime of CFC-11, 65 years in the RCW case, was varied from 55 to 75 years. Increases or decreases in the atmospheric concentration of CFC-11, however, tend to be offset by corresponding decreases or increases in atmospheric concentrations of other trace gases, such as other CFCs and CH_4.

[u] The amount of stratospheric ozone depletion due to chlorine contained in CFCs was increased from a 0.03% to 0.20% decline in total column ozone/$(ppb)^2$ of stratospheric chlorine.

[v] The rate at which tropospheric ozone forms as a result of CH_4 abundance was increased. In the RCW case, this variable for the Northern Hemisphere is a 0.2% change in tropospheric ozone for each percentage change in CH_4 concentration; it was changed to 0.4% in the sensitivity analysis.

[w] Tropospheric OH formation is affected by the level of NO_x emissions. A 0.1% OH change for every 1% change in NO_x emissions for the Northern Hemisphere was assumed in the RCW case; in the sensitivity analysis, a range of 0.05% to 0.2% was evaluated.

[x] For this analysis we assumed that a 2°C increase in realized warming would alter ocean circulation patterns sufficiently to shut off net uptake of CO_2 and heat by the oceans.

TABLE 6-1 -- NOTES (continued)

[y] We assumed that with each 1°C increase in temperature, an additional 110 Tg CH_4 from methane hydrates, 12 Tg CH_4 from bogs, and 7 Tg CH_4 from rice cultivation would be released.

[z] This case illustrates the combined impact of several types of biogeochemical feedbacks: 1) methane emissions from hydrates, bogs, and rice cultivation (see footnote above); 2) increased stability of the thermocline, thereby slowing the rate of heat and CO_2 uptake of the deep ocean by 30% due to less mixing; 3) vegetation albedo, which is a decrease in global albedo as a result of changes in the distribution of terrestrial ecosystems by 0.06% per 1°C warming; 4) disruption of existing ecosystems, resulting in transient reductions in biomass and soil carbon at the rate of 0.5 Pg C per year per 1°C warming; and 5) CO_2 fertilization, which is an increase in the amount of carbon stored in the biosphere in response to higher CO_2 concentrations by 0.3 Pg C per ppm.

INTRODUCTION

The Rapidly Changing World and Slowly Changing World scenarios presented in Chapter V describe two significantly different futures for the global community. Although these two potential paths capture a wide range of uncertainty, they do not represent all possible outcomes. Alternative assumptions are clearly possible for many of the parameters specified in these scenarios; these alternative specifications could alter the timing and magnitude of global climate change described in the Rapidly Changing World and Slowly Changing World scenarios. To understand the importance of these alternative assumptions, this chapter examines how changes in key parameters affect our portrayal of the rate and magnitude of global climate change. These sensitivity analyses include alternative assumptions about: the magnitude and timing of global policies to combat climate change, rates of technological change, trace-gas source strengths and emission coefficients, the carbon cycle, sensitivity of the climate system, atmospheric chemistry, and feedbacks.

The sensitivity analyses discussed in this chapter are generally run relative to the Rapidly Changing World scenario, unless specified otherwise. Overviews of each case are provided to describe the basic results for the reader; more detailed discussion of the sensitivity analyses are provided in Appendix C.

ASSUMPTIONS ABOUT THE MAGNITUDE AND TIMING OF GLOBAL CLIMATE STABILIZATION STRATEGIES

The analyses of the Stabilizing Policy scenarios presented in this Report are based on the assumption that the global community takes immediate, concerted action to contend with the consequences of climate change. Potential actions, which are discussed in Chapters VII - IX, include reducing the amount of energy required to meet the world's increasing needs, developing alternative technologies that do not require the consumption of fossil fuels, halting deforestation, and making changes in agricultural practices, among others. For many reasons, however, the world may not respond to the threat of climate change in a timely fashion. This section explores the consequences of other possibilities, particularly the unwillingness or inability of some countries to participate in climate stabilization programs and the implications of delaying global action until a later date.

No Participation by the Developing Countries

Most of the greenhouse gas emissions currently committing the world to climate change can be traced to activities by the industrialized countries. Although the quantity of emissions generated by developing countries has been increasing, the argument is sometimes made that since the greenhouse problem has been largely caused by the industrialized countries, these countries should be responsible for solving the problem. Also, despite the potential environmental consequences of global climate change, other problems facing the developing countries, such as poverty, inadequate health care, and other apparently more pressing environmental problems may make it difficult for developing countries to commit any resources to climate stabilization policies.

Regardless of the merits of these arguments, for this sensitivity analysis we have assumed that developing countries do not participate in any climate stabilization activities; that is, only developed countries adopt policies to limit global climate change. For this analysis the developing countries include China and Centrally-planned Asian economies, the Middle East, Africa, Latin America, and South/Southeast Asia. We have assumed that industrialized countries (i.e., the U.S., the rest of the OECD countries, and the USSR and Eastern Europe) follow the path assumed in the Rapidly Changing World with Stabilizing Policies (RCWP) scenario, while developing countries follow the path assumed in the Rapidly Changing World No Response (RCW) case, in which the entire global community does not respond to climate change.

Even if developing countries do not participate in global stabilization policies, however, policies adopted by the industrialized countries are likely to lead to technological advancements, altered market conditions, etc., that indirectly reduce emissions in the developing countries as well. For example, advancements by the developed countries in automobile fuel efficiency or fuel supply technologies may be partly adopted by the developing countries, tangentially allowing for some climate stabilization benefits. If the developing countries do not participate, however, they may tend to adopt technological advances more slowly and at a higher cost than if they had participated from the start. This slower rate of technological diffusion could occur for many reasons -- for example, if the industrialized countries take actions that prevent easy access to improved technologies or they are unwilling or unable to make the necessary capital available for investment, or if developing countries decide to invest their limited resources in other areas.

Since we cannot be certain of the direction that non-participation by the developing countries might take, we analyzed two cases to capture the potential range of likely possibilities. In the first case, little technological diffusion was assumed, resulting in a future path of energy consumption and investment trends for developing countries similar to those assumed in the RCW scenario. In the second case, developing countries were assumed to have greater access to the efficiency improvements and technological advances assumed for the RCWP case as a result of policies by the industrialized countries to make these improvements available and extend the credit necessary for investment by the developing countries in these improvements.

In this analysis key assumptions for the developing countries included the following: (1) rates of energy efficiency improvements for all sectors are the same as in the RCW case or midway between the RCW and RCWP case; for example, automobile efficiency levels, which by 2050 in developing countries were 5.9 liters/100 km (40 mpg) in the RCW case and 3.1 liters/100 km (75 mpg) in the RCWP case, were varied from 5.9-4.1 liters/100 km (40-58 mpg); (2) CFCs are not phased out (although compliance with the Montreal Protocol would still occur); (3) agricultural practices that cause methane emissions from rice and enteric fermentation and nitrous oxides from fertilizers do not change or would show modest improvements; (4) deforestation continues as in the RCW case with an exponential decline in forest area; (5) non-fossil energy supply technologies developed by the industrialized countries are available to developing countries at a later date and a higher cost than assumed in the RCWP case; for example, technological diffusion of biomass gasification technology would occur 10 years later than it would in the RCWP case, but feedstock costs would remain high due to a lack of investment by the developing countries in highly productive energy plantations; and (6) no additional incentives are provided for increased use of natural gas.

Without the participation of the developing countries to stabilize the atmosphere, the amount of greenhouse gas emissions will increase substantially: In the analysis considered here, CO_2 emissions are 3-4 Pg C higher than in the RCWP case by 2050 and 6-13 Pg C higher by 2100 (emissions by 2100 are 8.1 to 14.7 Pg C lower than in the RCW case since industrialized countries adopt climate stabilization policies); [1] other greenhouse gas emissions are also higher. These emission increases are sufficient to increase realized warming by 0.4-0.6°C in 2050 compared with the RCWP case and 1.0-2.1°C by 2100 (see Figure 6-1), with equilibrium warming by 2100 up to 1.4-4.1°C higher. Figure 6-1 also shows the results for the Slowly Changing World scenarios. In this scenario, emission increases are sufficient to increase realized warming by 0.3-0.5°C in 2050 compared with the SCWP case and 0.6-1.1°C by 2100, with equilibrium warming by 2100 up to 0.8-2.0°C higher.

The implications of these results are clear: even if the industrialized countries adopt very stringent policies to counteract the effects of climate change, the atmosphere continues to warm at a rapid rate. As a result, unilateral action by the industrialized countries can significantly slow the

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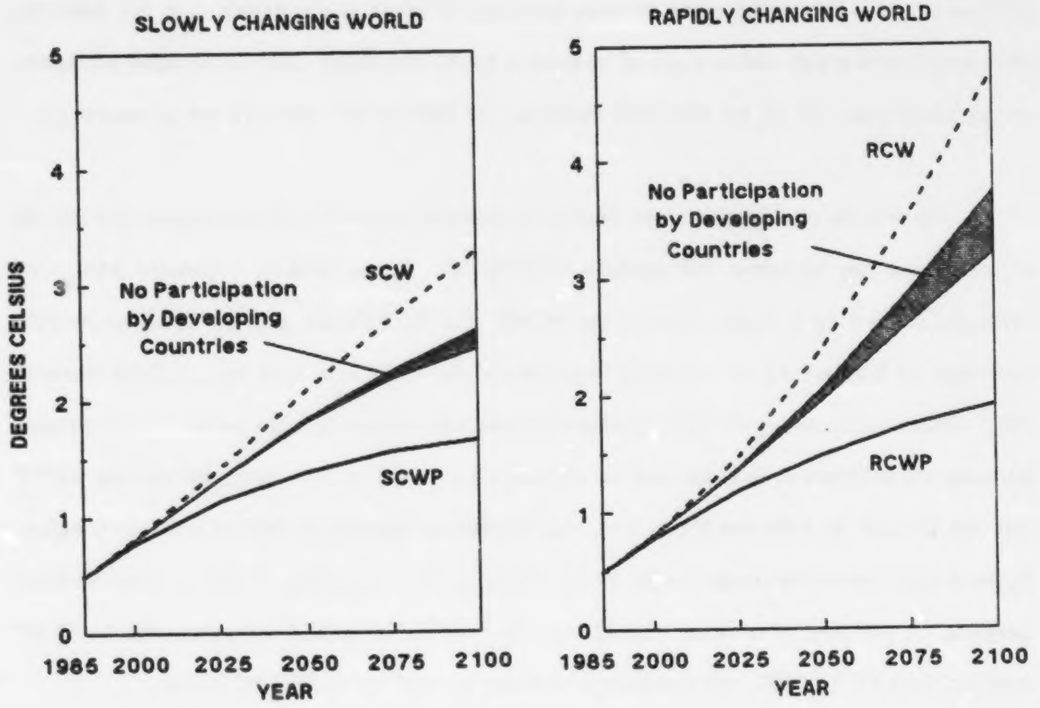
[1] Pg = petagram; 1 petagram = 10^{15} grams.

FIGURE 6-1



INCREASE IN REALIZED WARMING WHEN DEVELOPING COUNTRIES DO NOT PARTICIPATE

(Degrees Celsius; Based on 3.0 Degree Sensitivity)

rate and magnitude of climate change, but because of the growing impact that developing countries have on the global climate, without the participation of the developing countries, substantial global warming is unavoidable. Because most of the world's population resides in these countries, their role in climate stabilization becomes increasingly important as the demand for resources to feed and clothe their growing population and improve their standard of living expands.

Delay in Adoption of Policies

For the Stabilizing Policy cases presented in Chapter V it is assumed that the global community takes immediate action to respond to the dangers posed by climate change. For this sensitivity analysis we have assumed that the global community delays any response to the threat of climate change, with developed countries (i.e, the United States, the rest of the OECD countries, the USSR and centrally-planned European economies) delaying action until 2010, and the developing countries delaying action until 2025. Additionally, once regions do initiate action to combat global warming, they do so at a slower rate than assumed in the RCWP case. This slower approach assumes a minimum 25-year delay in attaining the policy goals of the RCWP case; that is, levels of technological improvement, availability of alternative energy supply technologies, etc., will be achieved at least 25 years later. For example, in the RCWP case, automobile efficiency reaches 3.1 liters/100 km (75 mpg) by 2050; in the Delay case industrialized countries reach 3.9 liters/100 km (60 mpg) by 2050, while developing countries reach 4.7 liters/100 km (50 mpg); the rate of energy efficiency improvement for the residential, commercial, and industrial sectors is unchanged from the rates assumed in the RCW case, through 2010 for industrialized countries and 2025 for developing countries. After these years, energy efficiency improvements occur at the same rate assumed in the RCWP case; and the implementation of production and consumption taxes on fossil fuels from the RCWP case was delayed until 2010 for developed countries and 2025 for developing countries.

Delaying the adoption of policies to stabilize the atmosphere significantly increases the Earth's commitment to global warming. With delay by the industrialized countries until 2010 and by the developing countries until 2025, the increase in realized warming compared to that assumed in the RCWP case is 0.4-0.6°C by 2050 and 0.5-0.9°C by 2100; equilibrium warming is 0.6-1.2°C higher by 2050 and 0.7-1.4°C higher by 2100 (based on climate sensitivities of 2.0-4.0°C; see Figure 6-2). Figures 6-2 also shows the results for the Slowly Changing World scenarios. If global delays do occur, the increase in realized warming compared to that assumed in the SCWP case is 0.3-0.5°C by 2050 and 0.3-0.6°C by 2100; equilibrium warming is 0.5-0.9°C higher by 2050 and 0.4-0.8°C higher by 2100 (based on climate sensitivities of 2.0-4.0°C).

ASSUMPTIONS AFFECTING RATES OF TECHNOLOGICAL CHANGE

The extent of global warming will depend on the availability of energy supplies and technologies that minimize dependence on carbon-based fuels, nitrogen-based fertilizers, and other sources of greenhouse gas emissions. The availability of non-fossil fuel technologies and the development of new production methods that significantly increase the supply of natural gas could have an impact on the rate of change in greenhouse gas emissions. Alternative assumptions regarding these factors are presented below.

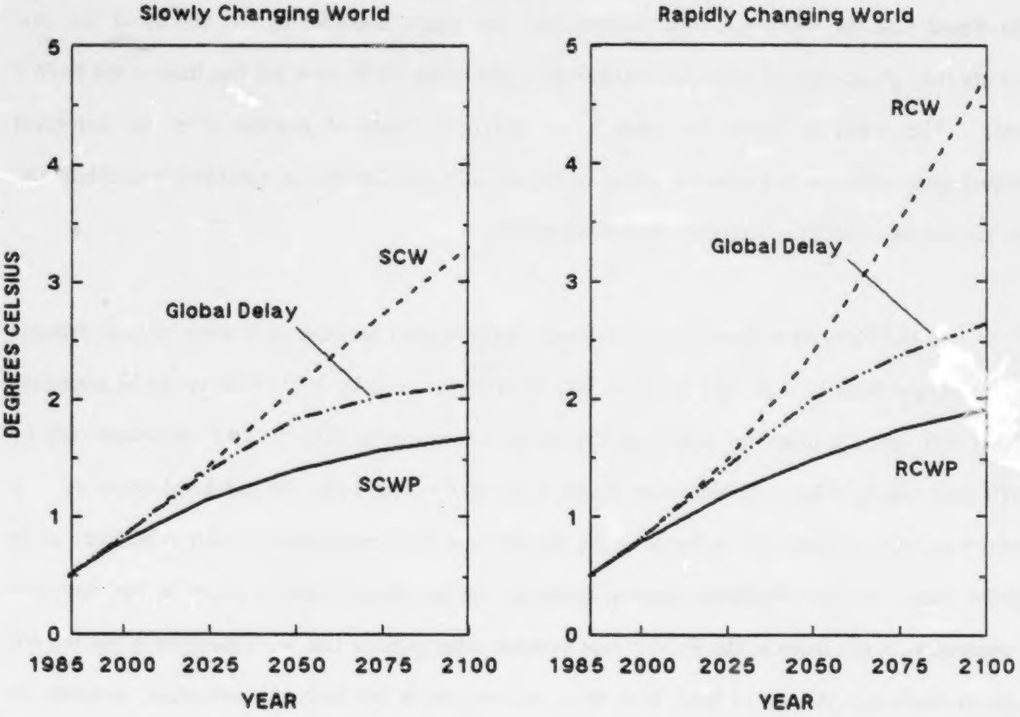
Availability of Non-Fossil Technologies

Most technologies in use currently rely on fossil fuels to supply their energy needs. In the Rapidly Changing World, fossil-fuel-based technologies continue to dominate throughout the next century: by 2100 fossil fuels still supply over 70% of primary energy needs. However, if non-fossil technologies can be commercialized earlier, the magnitude of global climate change can be reduced because these technologies do not emit the greenhouse gases that cause global warming. To evaluate

FIGURE 6-2

INCREASE IN REALIZED WARMING
DUE TO GLOBAL DELAY IN POLICY ADOPTION

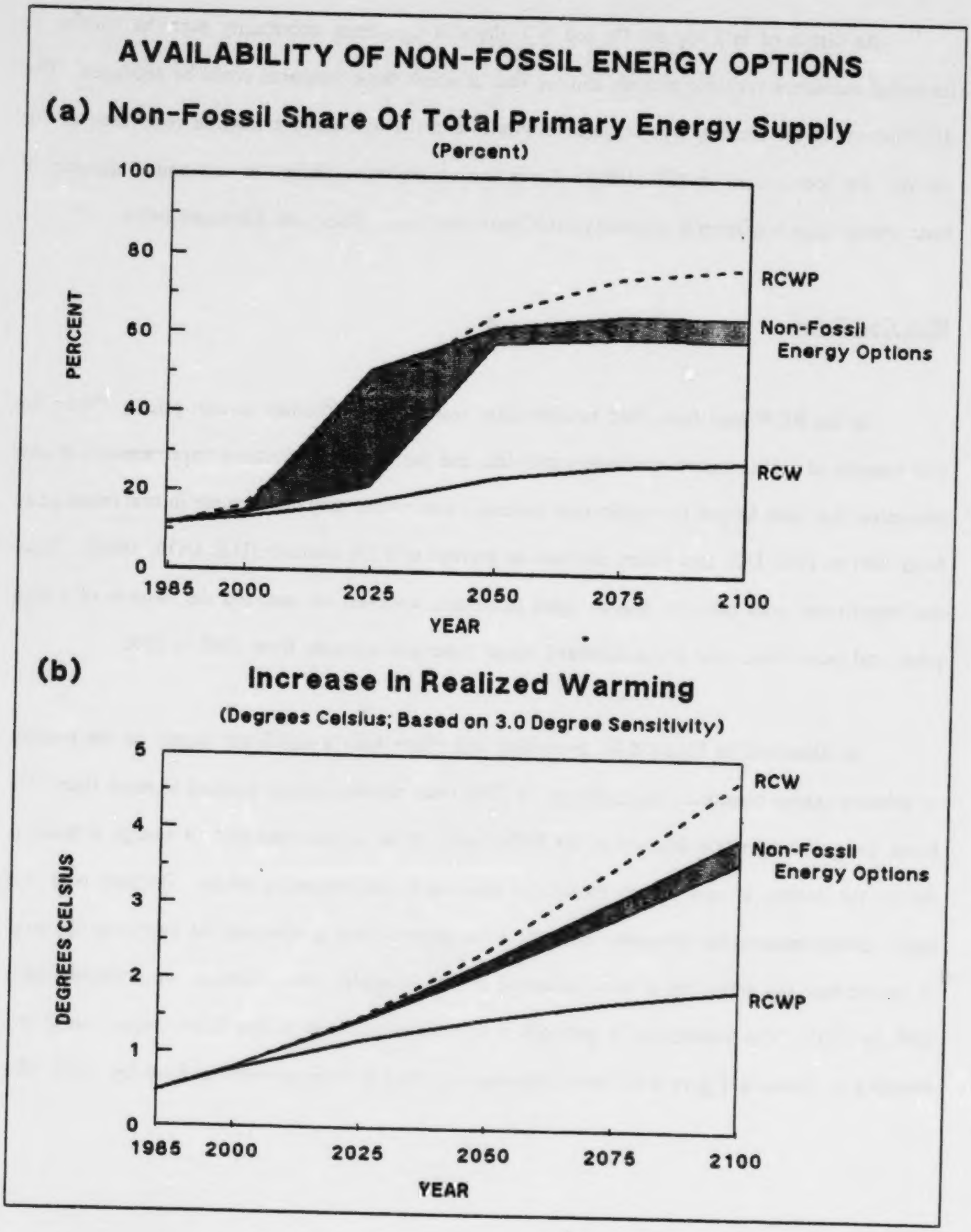
(Degrees Celsius; Based on 3.0 Degree Sensitivity)



the implications of the availability of non-fossil technologies, two different scenarios were analyzed: (1) an Early Non-Fossil case, in which non-fossil technologies, specifically solar photovoltaics, advanced nuclear power designs, and production of synthetic fuels from biomass, are commercially available by 2000 at a rate faster than that assumed in the RCWP case; and (2) an Intermediate Non-Fossil case, in which non-fossil technologies are widely available by the middle of the next century (i.e., greater use of non-fossil technologies than in the RCW case, but less than in the RCWP case). The intent of these two cases is to capture a range of possible roles for non-fossil technologies, with the first case reflecting very optimistic assumptions on non-fossil availability and the second case reflecting more modest assumptions.

In the Early Non-Fossil case, non-fossil energy sources increase their share of total primary energy supply from 12% in 1985 to about 50% by 2025 and 65% by 2100, while in the Intermediate Non-Fossil case the share for non-fossil technologies increases to 21% by 2025 and about 60% by 2100 (see Figure 6-3a). As shown in Figure 6-3a, in the near term the non-fossil share of total energy could be greater than reflected in the RCWP case if commercial availability is achieved at an earlier date. In this sensitivity analysis, however, the non-fossil share is lower in the long run compared with the share in the RCWP case because other policies that were included in the RCWP case to discourage the use of fossil fuels were not included in this case. In both cases, however, an increased role for non-fossil technologies can affect the amount of global warming. As shown in Figure 6-3b, for the two cases presented here the amount of realized warming compared with the RCW case could be reduced about 0.1-0.3°C by 2050 and 0.6-1.3°C by 2100; equilibrium warming could be reduced about 0.2-0.9°C by 2050 and 0.9-2.5°C by 2100 (based on 2.0-4.0°C climate sensitivities).

FIGURE 6-3


AVAILABILITY OF NON-FOSSIL ENERGY OPTIONS
(a) Non-Fossil Share Of Total Primary Energy Supply
(Percent)
PERCENT
100
80
60
40
20
0
1985
2000
2025
2050
2075
2100
YEAR
RCWP
Non-Fossil Energy Options
RCW
(b) Increase In Realized Warming
(Degrees Celsius; Based on 3.0 Degree Sensitivity)
DEGREES CELSIUS
5
4
3
2
1
0
1985
2000
2025
2050
2075
2100
YEAR
RCW
Non-Fossil Energy Options
RCWP

Cost and Availability of Fossil Fuels

As discussed in Chapters IV and VII, there is significant uncertainty over the amount of fossil-fuel resources available globally and the cost at which these resources could be produced. The development of the fossil energy resource estimates and the associated extraction costs used in this analysis are documented in ICF (1988). Given the uncertainties about the cost and availability of fossil energy supplies, several sensitivity cases were analyzed. These are discussed below.

High Coal Prices

In the RCW case from 1985 to 2050 there was no real escalation in coal prices. Given the vast quantity of coal resources available worldwide, and the rate of productivity improvements in coal extraction that have helped to contain cost increases, coal prices may not escalate in real terms (e.g., from 1949 to 1987, U.S. coal prices declined an average of 0.2% annually [U.S. DOE, 1988]). Since the longer-term price path for coal is highly uncertain, however, we analyzed the impacts of a high price coal case where coal prices escalated about 1 percent annually from 1985 to 2100.

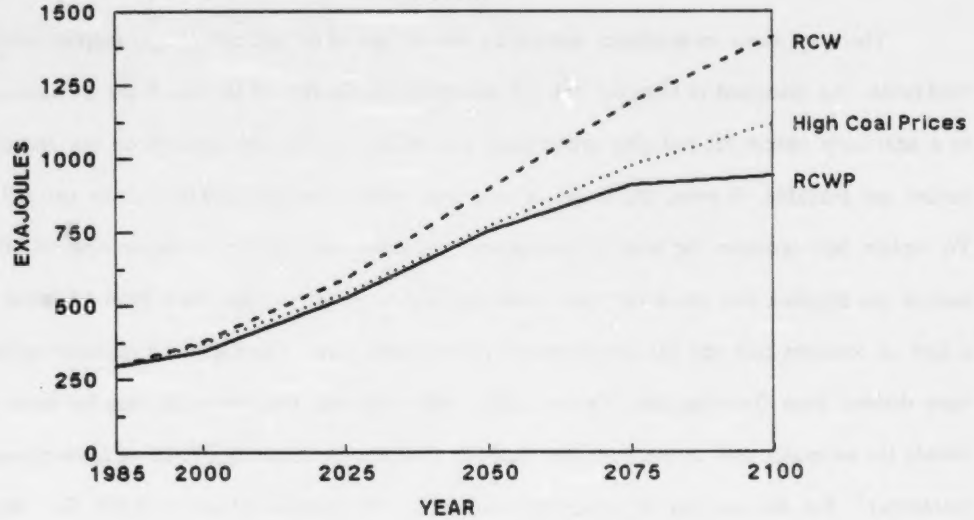
As illustrated in Figure 6-4a, increasing coal prices have a significant impact on the amount of primary energy consumed; for example, by 2100 total primary energy demand is more than 20% lower compared with this demand in the RCW case. Most of this reduction in energy demand is due to the decline in coal use as consumers respond to the escalating prices. Because coal is a major energy resource for electricity production and synthetic fuel production, the impact on the level of greenhouse gas emissions is fairly substantial. For example, CO_2 emissions are reduced nearly 50% by 2100. The reductions in greenhouse gas emissions have a significant impact on global warming, as shown in Figure 6-4b, which indicates a decline in realized warming from the RCW case

FIGURE 6-4

IMPACT OF 1% PER YEAR REAL ESCALATION IN COAL PRICES

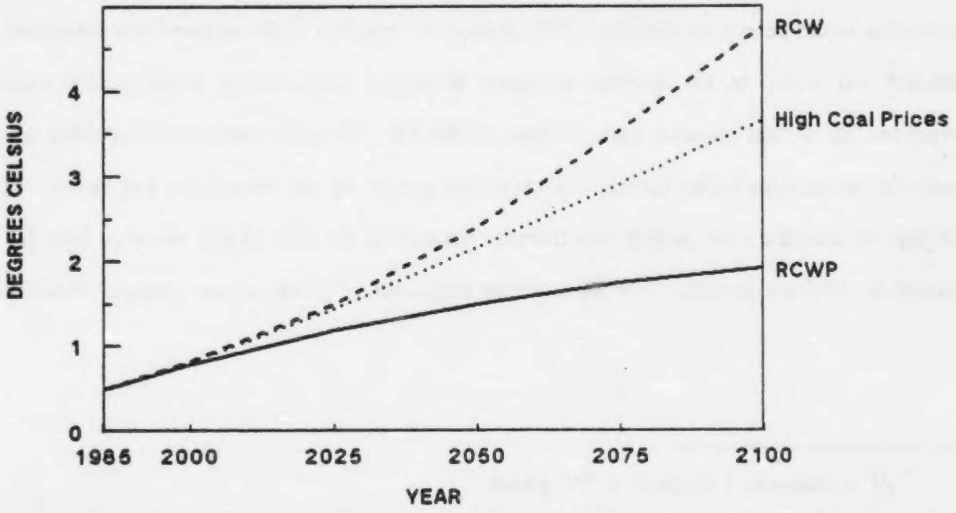
(a) Total Primary Energy Demand

(Exajoules)



(b) Increase In Realized Warming

(Degrees Celsius; Based on 3.0 Degree Sensitivity)



of 0.2-0.3°C by 2050 and 0.9-1.3°C by 2100 (assuming 2.0-4.0°C climate sensitivities). The corresponding decrease in equilibrium warming by 2100 is 1.3-2.5°C.

Alternative Oil and Natural Gas Supply Assumptions

There are many uncertainties concerning the amount of oil and natural gas supplies available worldwide. As discussed in Chapter VII, for example, the viability of increased use of natural gas as a near-term option for reducing greenhouse gas emissions critically depends on the amount of natural gas available, its price, the length of time over which adequate supplies can be secured, etc. To explore how sensitive the level of greenhouse gas emissions may be to the amount of oil and natural gas supplies, two sensitivity cases assuming higher global supplies have been analyzed: (1) a high oil resource case and (2) a high natural gas resource case. The higher oil resource estimates were derived from Grossling and Nielsen (1985), who indicated that resources may be more than double the estimates used in the base case analyses (which were about 12,000 EJ of conventional oil resources).[2] For this analysis we assumed conventional oil resources of about 25,000 EJ. Natural gas estimates were derived from Hay et al. (1988), which assumed in-place resources of about 150,000 EJ. For purposes of this sensitivity case, we assumed that technological improvements in gas extraction would permit an additional 10% of in-place resources to be economically recovered. This amount was added to the baseline estimates of proved reserves and economically recoverable resources, for a total resource base of about 27,000 EJ. We must emphasize that these sensitivity cases do not examine policy options that encourage greater oil and natural gas use; rather, they only attempt to examine how current uncertainties concerning the size of the resource base for these energy supplies can directly affect the rate and magnitude of global climate change. Policy options encouraging greater use of these fuels in conjunction with higher resource estimates would have a substantially different impact.

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[2] EJ = exajoule; 1 exajoule = 10^{18} joules.

High Oil Resources. An increase in global oil resources to 25,000 EJ is more than double the resource estimates assumed in the RCW case. These additional resources were assumed to be available at the same economic costs, such that the amount of oil available at any given price was twice the amount assumed in the RCW case. This increase in oil resources had two major impacts: (1) the amount of synthetic production of liquid fuels from coal declined substantially since conventional oil supplies were available at a competitive price to meet this demand; and (2) total demand for energy, mainly oil, increased as consumers responded to the increased availability of oil supplies at the same price (since twice the amount of oil was available at a price equal to that in the RCW case). The net effect of these impacts is a small increase in total primary energy demand (a 4% increase by 2050), a major shift from coal (primarily for synthetic fuel production) to oil, and a decrease in the portion of total primary energy supplied by non-fossil resources since oil is more plentiful and competitive; for example, non-fossil fuels supply about 22% of all energy by 2050 compared with 24% in the RCW case (see Figure 6-5). The net effect of these factors is an increase in CO_2 emissions of 0.4 Pg C by 2050 and 2.2 Pg C by 2100. The decline in coal production, however, lowered methane (CH_4) emissions since the amount of CH_4 emitted during coal mining decreased substantially (e.g., by 2100 CH_4 emissions from fuel production declined from about 360 Tg in the RCW case to 210 Tg), resulting in a modest decline of less than 0.1°C in realized warming by 2100 compared with the RCW case warming (assuming 2.0-4.0°C climate sensitivities).[3]

High Natural Gas Resources. For the high natural gas resource case, natural gas resources were increased from about 10,000 EJ to 27,000 EJ. As in the high oil resource case, higher natural

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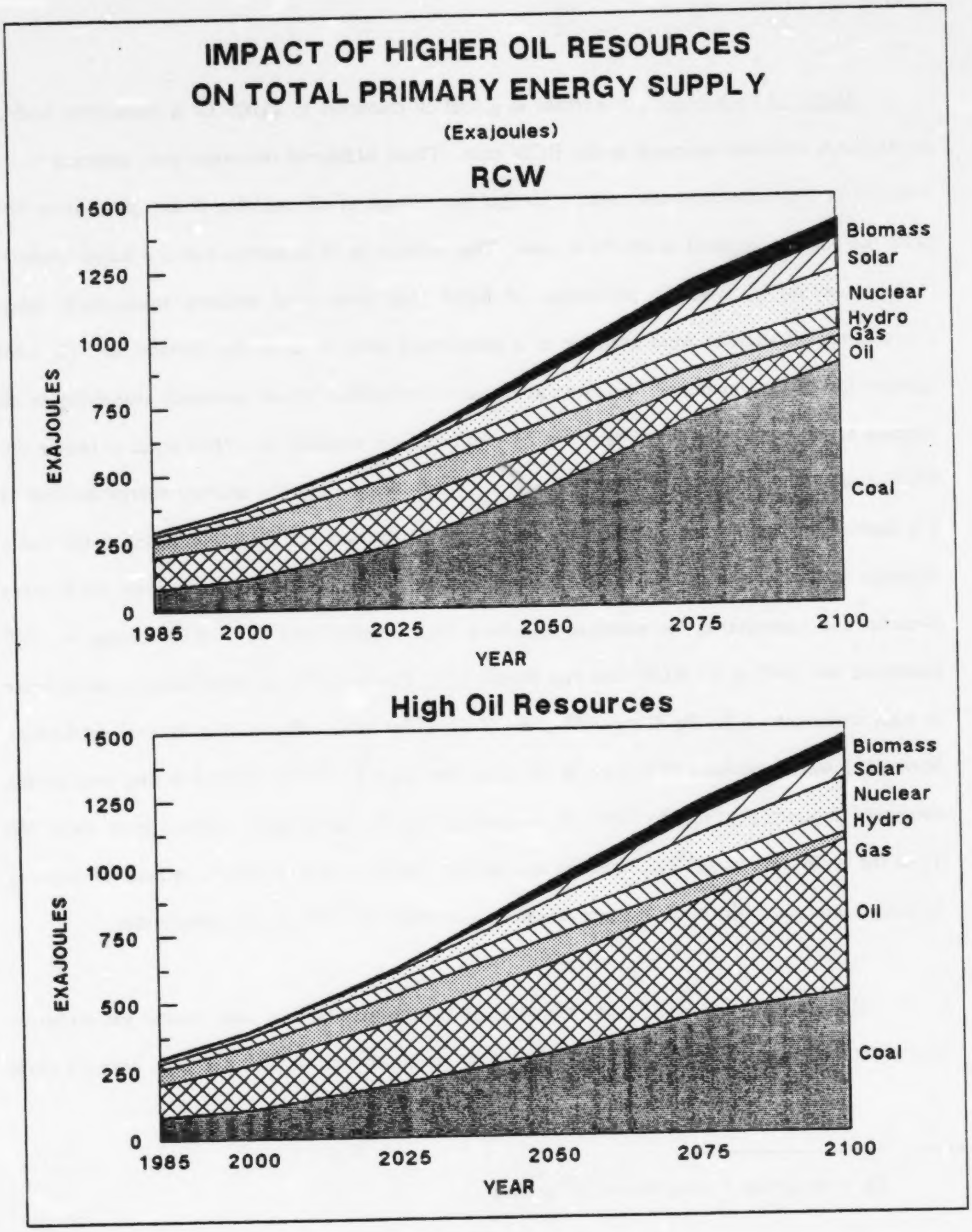
[3] Tg = teragram; 1 teragram = 10^{12} grams.

FIGURE 6-5

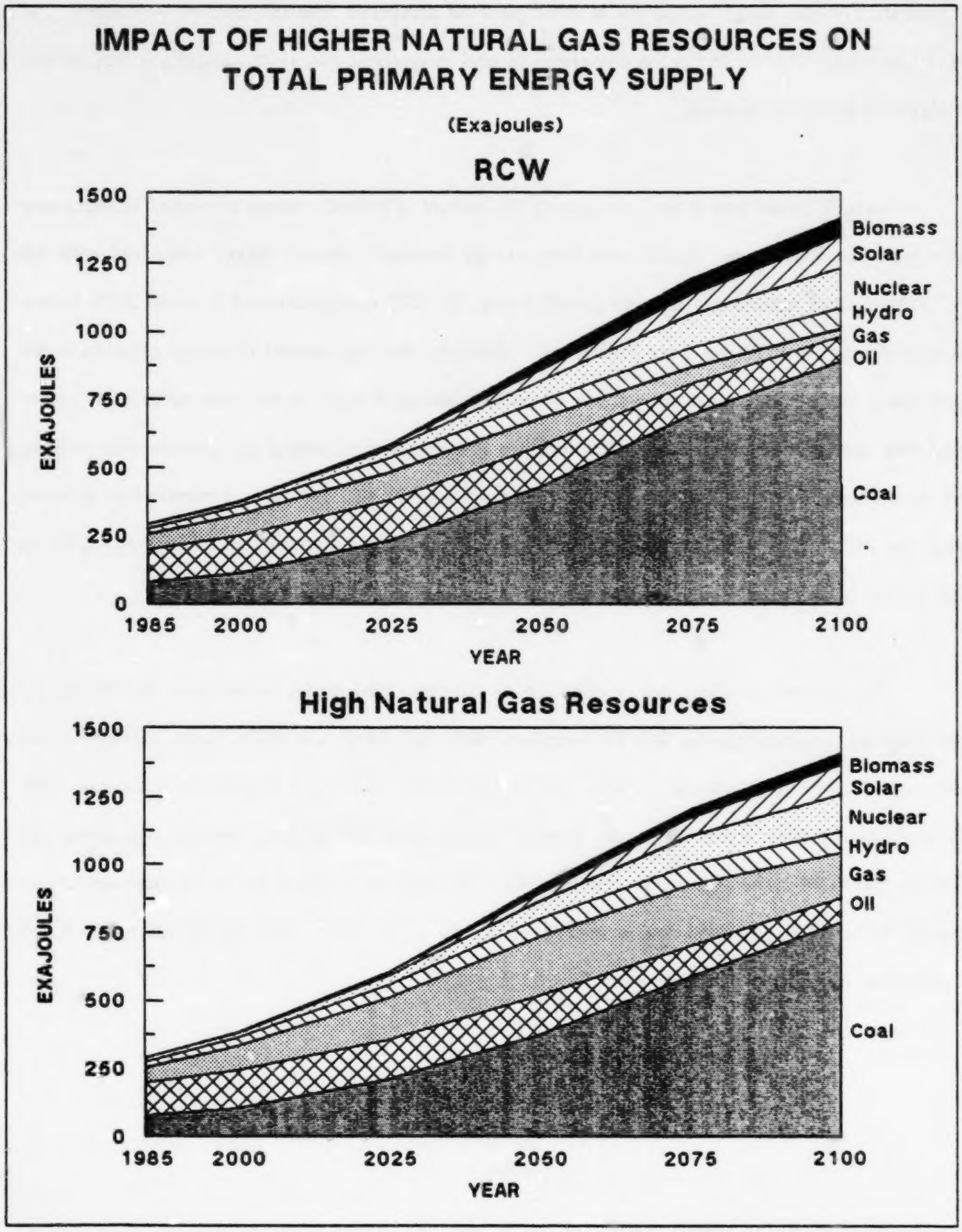

IMPACT OF HIGHER OIL RESOURCES
ON TOTAL PRIMARY ENERGY SUPPLY
(Exajoules)
RCW
EXAJOULES
1500
1250
1000
750
500
250
0
1985
2000
2025
2050
2075
2100
YEAR
Biomass
Solar
Nuclear
Hydro
Gas
Oil
Coal
High Oil Resources
EXAJOULES
1500
1250
1000
750
500
250
0
1985
2000
2025
2050
2075
2100
YEAR
Biomass
Solar
Nuclear
Hydro
Gas
Oil
Coal

gas resource estimates result in two major impacts: (1) an increase in demand for energy, particularly for gas, since natural gas is more plentiful compared with the amount available in the RCW case; and (2) a decline in the conversion of coal to synthetic gas, since natural gas supplies are available to meet the demand.

Overall, by the end of the 21st century the amount of primary energy consumed changes very little from the RCW case. In the near term energy demand increases slightly compared with the RCW case, since natural gas is more plentiful (e.g., by 2025 energy demand is about 2.5% higher compared with the RCW case; see Figure 6-6). However, the total amount of energy required in the long run is less because a greater portion of end-use energy demand is met with natural gas rather than with synthetic gas from coal. This increase in conventional natural gas consumption reduces the total primary energy required to satisfy demand because the decline in synthetic fuel demand from the RCW case reduces the amount of energy required for synthetic fuel conversion, although this impact is small: by 2100 primary energy demand is lower by less than 1%.

The amount of natural gas consumed does increase significantly; for example, in 2050 natural gas consumption increases to 215 EJ compared with 100 EJ in the RCW case. However, the increased availability of natural gas also reduces the portion of energy supplied by non-fossil fuels; for example, by 2050 non-fossil energy sources supply about 20% of total demand compared with 24% in the RCW case. The net impact on CO_2 emissions due to these factors is quite small: no change in emissions by 2050 and a decline of 0.7 Pg C by 2100. The impact on realized and equilibrium warming is negligible (less than 0.1°C).

FIGURE 6-6



IMPACT OF HIGHER NATURAL GAS RESOURCES ON TOTAL PRIMARY ENERGY SUPPLY

(Exajoules)

RCW

High Natural Gas Resources

Availability of Methanol-Fueled Vehicles

The transportation sector throughout the world is heavily dependent on petroleum-based fuels. This dependence, particularly on gasoline and diesel fuel, produces substantial quantities of greenhouse gases (see Chapter IV). A variety of non-petroleum-based alternatives are under development, including the use of methanol. There are many potential advantages to using methanol as a transportation fuel rather than gasoline; according to recent research, advanced methanol-fueled vehicles could be 20-40% more energy efficient, emit much lower levels of CO, and reduce non-methane hydrocarbon (NMHC) reactivity up to 95% (Gray, 1987). Methanol's potential to reduce NMHC reactivity could reduce levels of urban ozone, which would improve ambient air quality in urban areas. These reductions could be on the order of about 5-20% of peak ozone levels (DeLuchi et al., 1988). However, it is not clear how reductions in urban ozone levels may translate to reductions in average tropospheric ozone and, therefore, changes in radiative forcing. Current understanding of these atmospheric processes attributes urban ozone changes primarily to NMHC and NO_x flux, while tropospheric ozone changes depend primarily on (in descending order of importance) CH_4, CO, NO_x flux, and NMHC flux (Prather, 1988). Interactions between urban air quality and the rest of the troposphere cannot be evaluated with the aggregate model used here.

Since the ability of methanol to affect tropospheric ozone levels cannot be reliably estimated, we cannot reflect all of the potential advantages of using methanol as a transportation fuel. It is useful to note, however, that in addition to reducing emissions of CO and other gases, methanol can be produced from different types of feedstocks, such as natural gas, coal, or biomass. When biomass is the feedstock, the carbon emitted during the combustion process is recycled from the environment as the biomass is grown. As a result, the net CO_2 emissions are zero when biomass is used. Greenhouse gas emissions from methanol, however, can be greater than those from gasoline if coal is used as the feedstock because additional emissions will be generated during the methanol production process. According to one analysis, methanol production from coal would generate about twice the amount of CO_2-equivalent emissions (based on their radiative effect) compared to gasoline from crude oil, while methanol from natural gas would only be slightly better (about 3%) than petroleum-based fuels (DeLuchi et al. 1988). From a global warming perspective, DeLuchi et al. concluded that only biomass-derived methanol would substantially reduce the amount of radiative forcing from transportation fuels, although as mentioned above, this argument does not incorporate any potential benefits from reductions in urban ozone levels.

ATMOSPHERIC COMPOSITION: COMPARISON OF MODEL RESULTS TO ESTIMATES OF HISTORICAL CONCENTRATIONS

The atmospheric composition model was applied to estimates of historical emissions of trace gases and the results compared to historical data on atmospheric composition. This exercise provides insight on how the model performed under conditions much different from the reference year, 1985, and provided one mechanism to validate the model. The exercise included the development of a single scenario of historical emissions of trace gases and application of the model using different assumptions on climate sensitivity and chemistry parameters in the model.

The scenario of historical emissions of trace gases is based on estimates of natural sources from the Atmospheric Stabilization Framework described in Chapter V, estimates from a study by Darmstadter et al. (1987) on historical emissions from various anthropogenic sources, and estimates of historical CO_2 emissions from Rotty (1987) and Houghton (1988). For natural emission sources, historical emissions were assumed to be constant from 1870 to 1985 at the levels assumed in the scenarios described in Chapter V. The exception is emissions of CH_4 from wetlands, which were assumed to be larger in 1870 by 50% and to decline to current levels due to destruction of wetlands.

The estimates of historical emissions of CFCs and Halons were taken from EPA's Regulatory Impact Analysis on Stratospheric Ozone Protection (U.S. EPA, 1988).

The alternative scenarios of historical atmospheric composition and global warming reflect a range of assumptions concerning the climate sensitivity and the first and second order relationships assumed in the model. Figure 6-7 illustrates the increase in realized warming projected from 1840 to 1985, which ranges from 0.4°C to 0.8°C based on a range of climate sensitivities (from 1.5 to 5.5°C for doubled CO_2). These results compare well with results from Wigley et al. (1986), who estimated a global temperature increase of 0.3-0.7°C in the last century, and Hansen et al. (1988), who estimated a global temperature increase of 0.4-0.8°C during the same period. The model produced estimates of atmospheric concentrations of CO_2, CH_4, N_2O, CO, and CFC-12 within 1.5% and estimates of concentrations of CFC-11 within 3.5% of observed values in 1985. In addition, the pattern of estimated atmospheric concentrations over time conformed well with historical measurements for CO_2, N_2O, and CH_4. Estimates of concentrations of some gases such as CFC-22 varied from the historical measurements to a greater extent, which reflects their more recent introduction and rapid growth in atmospheric concentrations. Table 6-2 summarizes the results for the long-lived gases.

For CO_2, the atmospheric concentration over time matched the Mauna Loa and Ice Core measurements by design through the use of the unknown sink in the model (see **Unknown Sink in Carbon Cycle**). The unknown sink is zero through 1940 and then slowly rises to 1.9 Pg C per year by 1985, which represents about one-third of the estimated anthropogenic emissions.

The estimates of CH_4 concentrations match atmospheric and ice core measurements well, especially given the uncertainties in the emissions estimates and the historical measurements. The model shows somewhat higher than expected growth in the late 19th century, which may reflect the

FIGURE 6-7

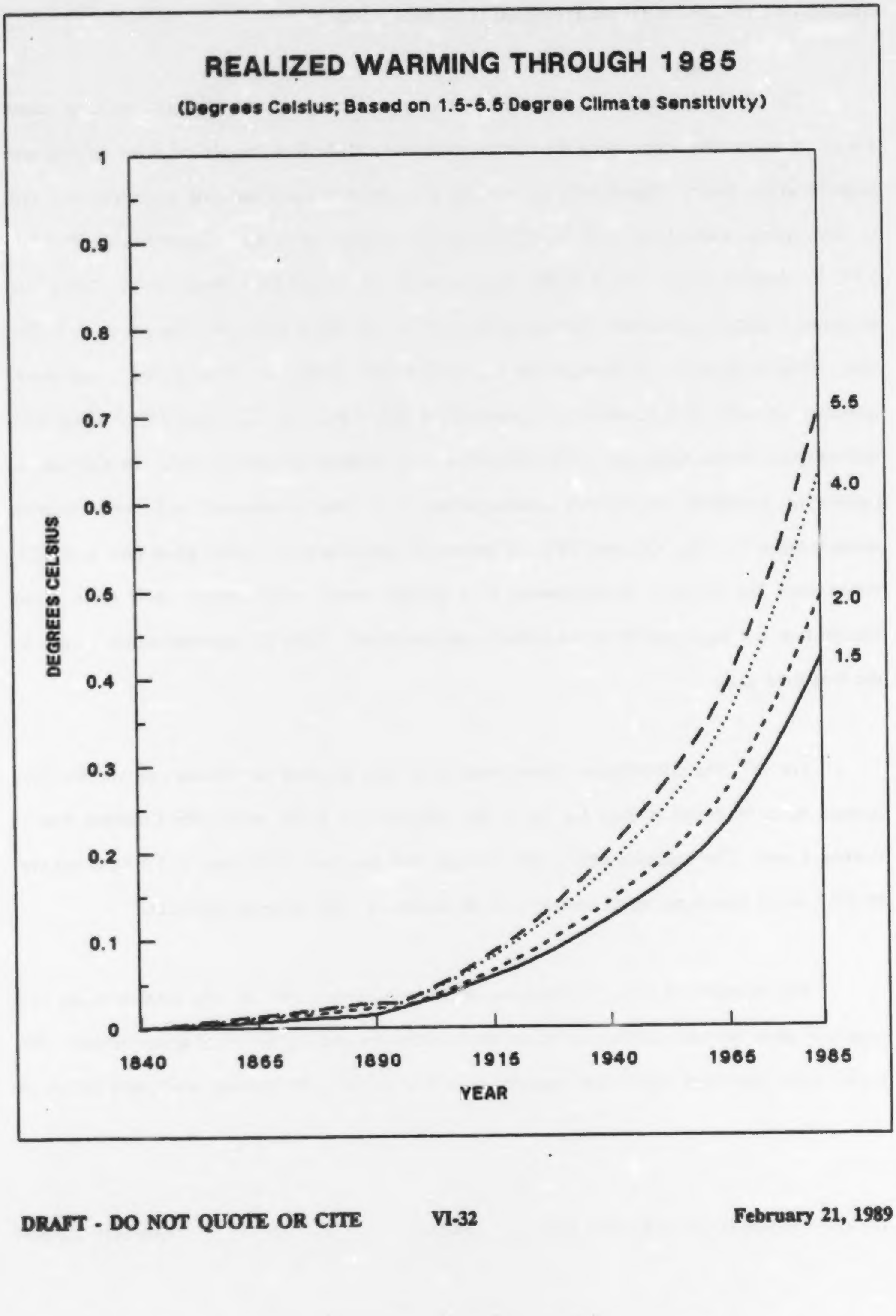

REALIZED WARMING THROUGH 1985
(Degrees Celsius; Based on 1.5-5.5 Degree Climate Sensitivity)
DEGREES CELSIUS
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1840
1865
1890
1915
1940
1965
1985
YEAR
5.5
4.0
2.0
1.5

TABLE 6-2
Comparison of Model Results to Concentrations in 1986

Trace Gas (units)	Model Results	Model Growth Rates	Atmospheric Measurements	Observed Growth Rates
CO_2 (ppm)	346	0.4%	346	0.4%
N_2O (ppb)	314	0.27%	310	0.2-0.3%
CH_4 (ppb)[a]	1650-1750	1%	1675	1%
CFC-11 (ppt)	212-222	4%	226	4%
CFC-12 (ppt)	391	4%	392	4%
HCFC-22 (ppt)	37	14%	100	7%
CCl_4 (ppt)[b]	70	0.6%	121	1.3%
CH_3CCl_3 (ppt)	186	12%	125	6%
Halon 1211 (ppt)	0.4	100%	2	>10%

---

[a] 1987 value.

[b] 1982 value.

uncertainties surrounding the scenario of historical emissions. Using the reference assumptions, the model achieves an atmospheric concentration of 1671 ppb in 1985 compared to the observed value of 1675 ppb. The CH_4 concentrations vary considerably in the sensitivity analyses and range from 1650 ppb to 1750 ppb for alternative chemistry parameters.

Of the three dominant greenhouse gases, the estimates of N_2O concentrations vary the most from historical measurements. The model predicts concentrations of 314 ppb in 1985 compared to 308 to 310 ppb cited in the literature. From 1979 to 1986, the model estimates growth in N_2O concentrations of 310 to 314 ppb compared to measurement data that suggests growth of 303 to 310 ppb. One of the possible explanations of these results is that the relative share of emissions of N_2O from anthropogenic sources is larger than estimated in the model. A larger anthropogenic source combined with lower natural emissions or a shorter atmospheric life would be needed to reduce the overall concentrations and obtain the growth in concentrations seen from 1979 to 1986. These results suggest that the model may underestimate future atmospheric concentrations of N_2O.

The model "predicts" very little deviation from current levels for the short-lived gases, including OH, O_3, and CO. The results for levels in 1870 include higher levels of OH by 14-26%, lower levels of tropospheric O_3 by 19-29%, lower concentrations of CO by approximately 50%, and increased levels of upper stratospheric ozone by 4.5%.

ASSUMPTIONS ABOUT TRACE-GAS SOURCES AND STRENGTHS

Among the various greenhouse gases there is some uncertainty over the quantity of emissions that can be attributed to specific sources and the ability of these gases to modify the atmosphere. The most critical of these uncertainties are examined below.

Methane Sources

The available evidence on CH_4 indicates that annual production ranges from 400-640 Tg of methane (based on known sources and sinks, its atmospheric lifetime, and current atmospheric concentrations). Within this budget, however, there is much dispute over the size of individual sources. For example, research indicates that current CH_4 emissions from rice paddies could be 60-170 Tg; similarly, estimated emissions from biomass burning range from 50-100 Tg (Cicerone and Oremland, 1989).

To account for these uncertainties, the initial CH_4 budget was varied to construct two cases: (1) a high anthropogenic impact case, where the starting methane budget was biased toward anthropogenic sources by assuming that anthropogenic activities such as fuel production and landfilling caused higher emission levels than assumed in the RCW case, while lower emission estimates were assumed from natural processes such as oceans, wetlands, wildfires, and wild ruminants; and (2) a low anthropogenic impact case, by assuming lower emissions from anthropogenic activities such as fuel production, enteric fermentation, and rice cultivation, with corresponding emission increases from natural processes such as oceans and wetlands. The specific emission assumptions for the starting budget are summarized in Table 6-3.

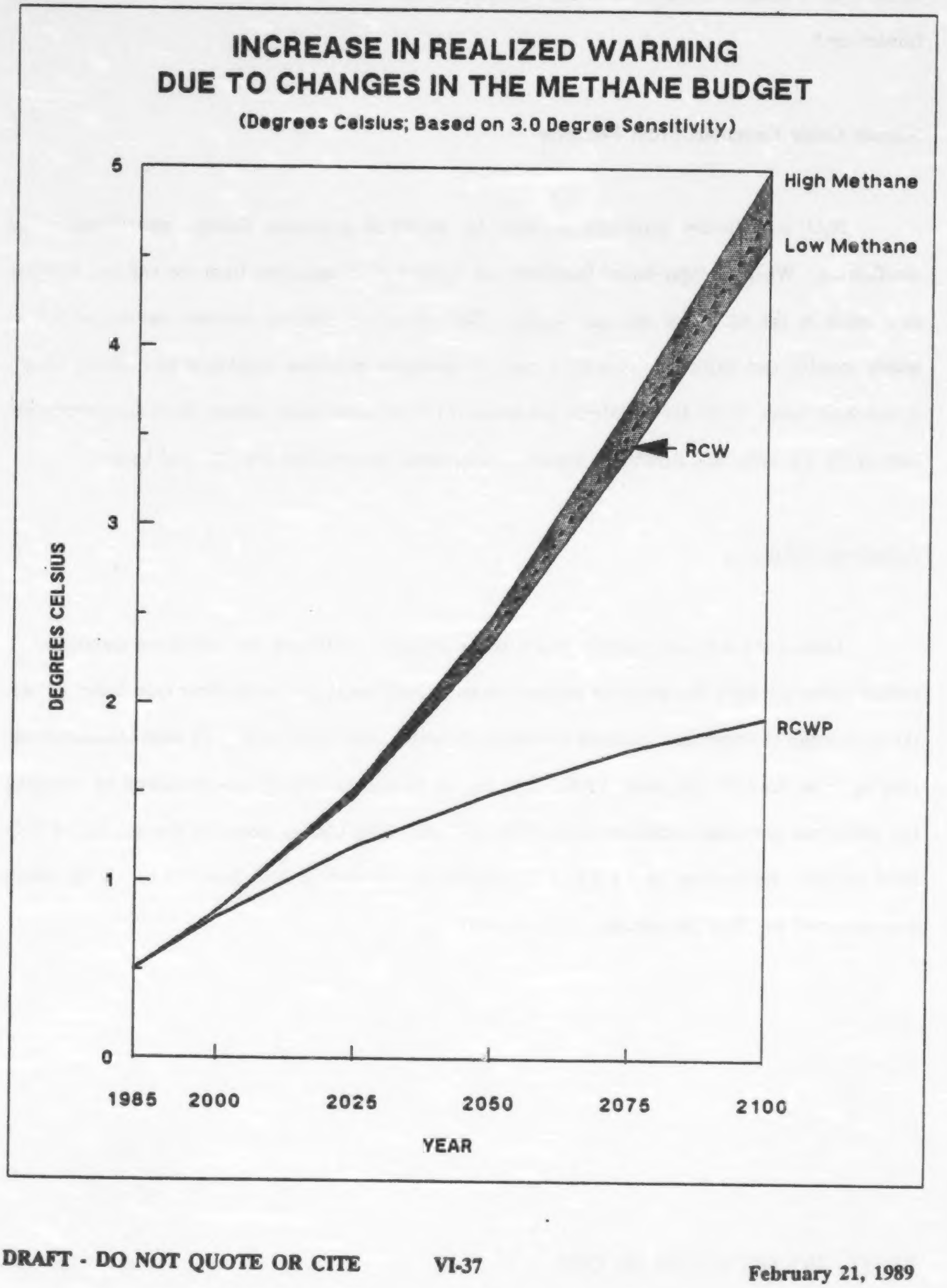
The alternative starting budgets in Table 6-3 result in different growth paths for CH_4, since emissions from anthropogenic sources increase by different amounts over time. These differences alter the atmospheric concentration of CH_4: by 2100 the atmospheric concentration is about 3500-3700 ppb in the Low Impact case and 5200-5500 ppb in the High Impact case (compared with 4100-4400 ppb in the RCW case). The increase (decrease) in CH_4 also increases (decreases) the amount of tropospheric ozone. The impact on realized warming is summarized in Figure 6-8, which indicates a decline of 0.1-0.2°C by 2100 in the Low Impact case compared with the RCW case and an increase

TABLE 6-3

Low and High Anthropogenic Impact Budgets For Methane
(teragrams/year as of 1985)

Source of Methane	Low Impact	RCW	High Impact
Fuel Production	50	60	95
Enteric Fermentation	70	75	75
Rice Cultivation	60	110	110
Landfills	30	30	58
Oceans	40	15	6
Wetlands	150	115	100
Biomass Burning--Anthropogenic	35	35	35
Biomass Burning--Natural	20	20	15
Wild Ruminants	44	44	10
Other Sources	11	6	6
TOTAL	510	510	510

FIGURE 6-8



INCREASE IN REALIZED WARMING DUE TO CHANGES IN THE METHANE BUDGET

(Degrees Celsius; Based on 3.0 Degree Sensitivity)

of 0.2-0.3°C by 2100 in the High Impact case. The corresponding effects on equilibrium warming by 2100 are a decline of 0.2-0.3°C in the Low Impact case and an increase of 0.3-0.5°C in the High Impact case.

Nitrous Oxide Emissions From Fertilizer

N_2O is naturally produced in soils by microbial processes during denitrification and nitrification. When nitrogen-based fertilizers are applied, N_2O emissions from the soil can increase as a result of the additional nitrogen source. The amount of fertilizer nitrogen evolved as N_2O is highly variable and uncertain. We have used the emission estimates developed by Galbally (1985) in our base cases: 0.5% for anhydrous ammonia, 0.1% for ammonium nitrate, 0.1% for ammonium salts, 0.5% for urea, and 0.05% for nitrates. Alternative assumptions are explored below.

Anhydrous Ammonia

One of the key uncertainties concerns the emission coefficient for anhydrous ammonia. A review of the scientific literature on measurements of N_2O emissions by fertilizer type indicates that the percentage of anhydrous ammonia evolved as N ranges from 0.05-6.84%, with most measurements ranging from 0.5-2.0% (Eichner, 1988). The impact of this uncertainty was evaluated by changing the anhydrous ammonia coefficient from 0.5% to 2.0%. This change increased the amount of N_2O from fertilizer applications by 0.1 Tg of N annually, an increase in 2025 from 0.7 to 0.8 Tg, which was too small to affect the amount of global warming.

N_2O Leaching From Fertilizer

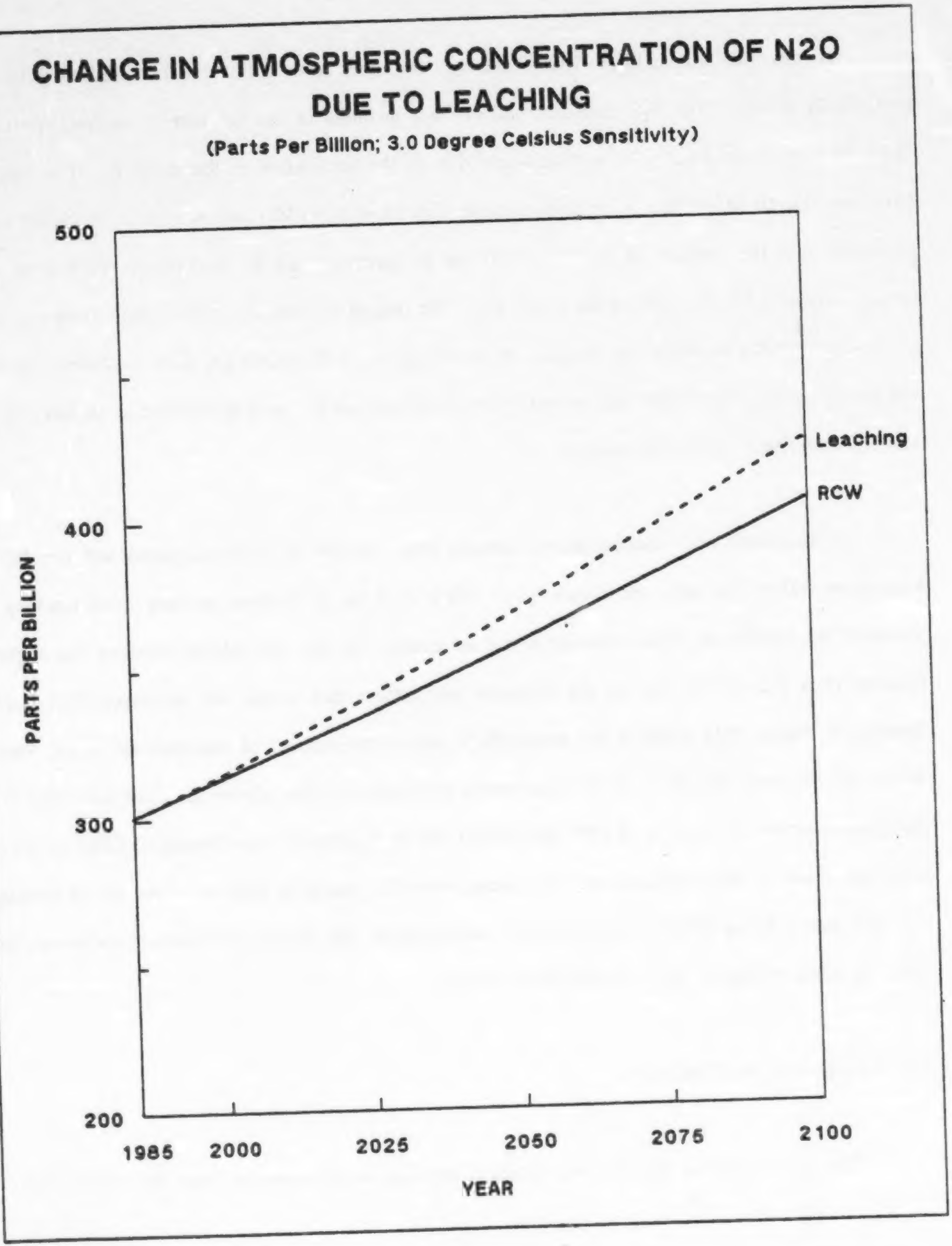
As discussed above, in the RCW case N_2O emissions from fertilizer were based on estimates by Galbally (1985). One N_2O emission pathway not included in this estimate is leaching from the fields into the ground water or surface water due to the application of the fertilizer. The rate of emissions related to leaching is highly uncertain; Conrad et al. (1983) and Kaplan et al. (1978) have suggested that the amount of N_2O evolved due to leaching may be as large as N_2O from the denitrification/nitrification processes in the soil. The impact of leaching on total N_2O emissions and the resulting global warming was analyzed by increasing all of Galbally's emission coefficients by one percentage point. The higher rate of N_2O from fertilizer due to leaching resulted in an increase in emissions of about 1.0-1.5 Tg annually.

Atmospheric N_2O concentrations increase about 20 ppb by 2100 compared with the RCW case (from 403 to 424 ppb; see Figure 6-9). While N_2O concentrations increase when leaching is assumed, the impact on global warming is not as certain. In this case, global warming was slightly reduced (less than 0.1°C) due to the chemical interactions that occur with increased N_2O levels. Specifically, higher N_2O levels in the stratosphere reduce the amount of stratospheric ozone, which in turn allows more ultraviolet (UV) radiation to penetrate to lower elevations. The increased UV radiation increases the amount of CFC destruction, which reduces the contribution of CFCs to global warming. None of these reactions are very strong, since the change in N_2O emissions due to leaching does not have a major effect on atmospheric concentrations, but they are sufficient to counteract the warming effect of higher N_2O concentrations alone.

N_2O Emissions From Combustion

During the combustion process, chemical interactions downstream from the combustion

FIGURE 6-9

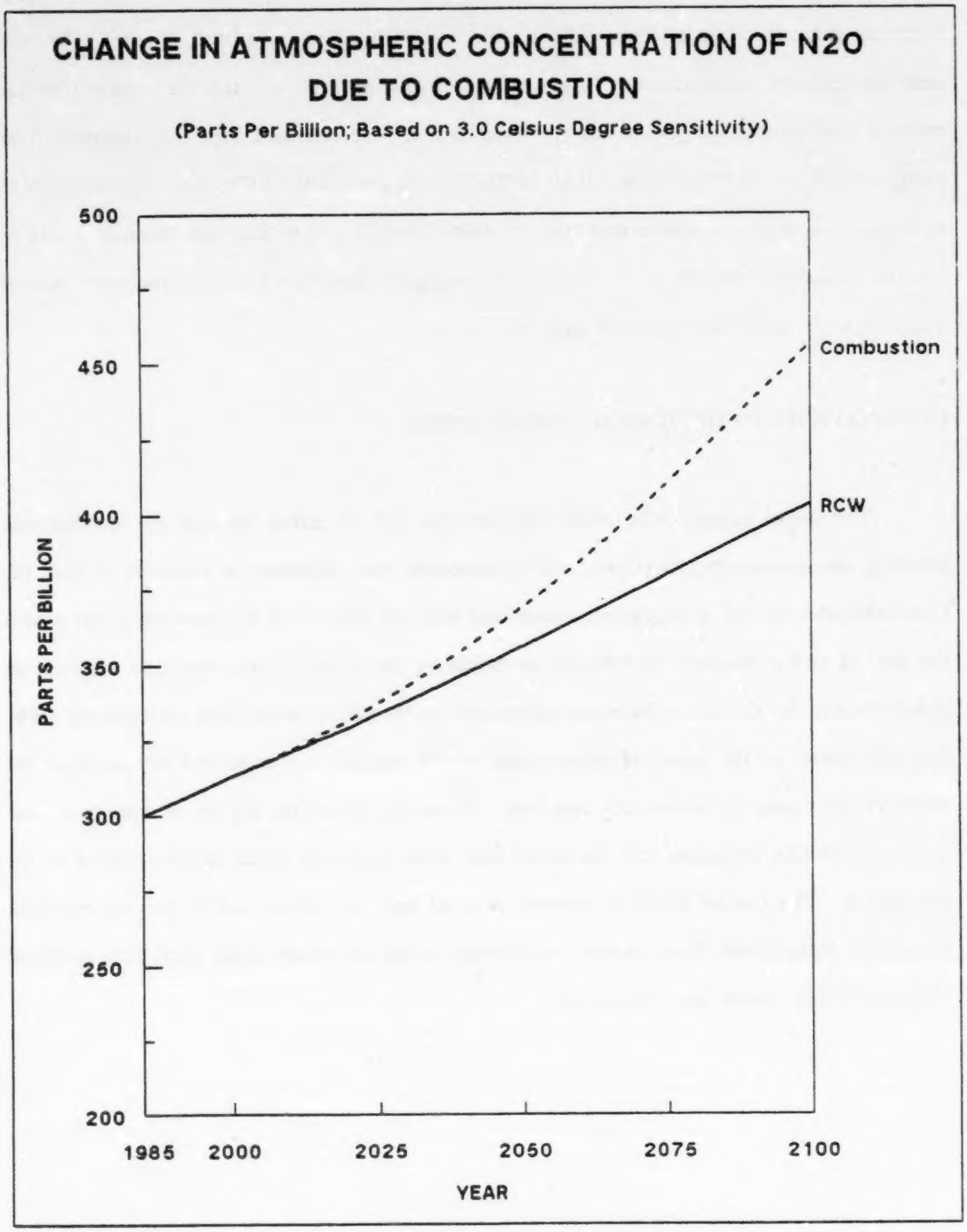

CHANGE IN ATMOSPHERIC CONCENTRATION OF N2O
DUE TO LEACHING
(Parts Per Billion; 3.0 Degree Celsius Sensitivity)
500
400
300
200
PARTS PER BILLION
1985
2000
2025
2050
2075
2100
YEAR
Leaching
RCW

chamber can lead to N_2O formation from nitrogen oxides. The rate of this formation is highly uncertain, although recent evidence indicates that it is likely to be fairly small. In the RCW case these low emission coefficients were assumed (see Chapter II). To ascertain the impact of higher emission coefficients, N_2O coefficients from combustion were increased such that emissions from energy in 1985 were 2.3 Tg N rather than 1.1 Tg N as obtained in the RCW case. The higher N_2O emission levels increased atmospheric concentrations about 50 ppb by 2100 (as shown in Figure 6-10); the resulting impact on global warming was negligible (less than 0.1°C) for the same reasons discussed above under leaching from fertilizer.

UNCERTAINTIES IN THE GLOBAL CARBON CYCLE

The global carbon cycle, which regulates the flow of carbon through the environment, including the atmosphere, biosphere, and hydrosphere, was discussed in Chapters II and III. Uncertainties in the size of the various sources and sinks for carbon and the interactions that govern the flow of carbon increase the difficulty of estimating the impact of anthropogenic activities on global climate. In this section the major uncertainties in the global carbon cycle are evaluated. The first part focuses on the impact of deforestation on CO_2 emissions. The second part discusses the ability of the oceans to absorb CO_2 and heat. Currently, the oceans are the dominant sink for anthropogenic CO_2 emissions, with the mixed layer alone containing about as much carbon as the atmosphere. The oceans' ability to operate as a net sink for carbon and heat is an important component of the global climate system; any changes in this absorption ability could have profound effects on global climate (see Chapter III).

FIGURE 6-10



CHANGE IN ATMOSPHERIC CONCENTRATION OF N2O DUE TO COMBUSTION

(Parts Per Billion; Based on 3.0 Celsius Degree Sensitivity)

Unknown Sink In Carbon Cycle

Atmospheric CO_2 concentrations have changed historically due to an imbalance between the sources and sinks for carbon. If the production of carbon exceeds the ability of the various carbon sinks to absorb it, then the atmospheric CO_2 concentrations will increase (and vice versa). When analyzing the amount of carbon produced from various sources in the past, atmospheric scientists have been unable to balance the carbon cycle. That is, given current estimates of carbon sources, it would appear that atmospheric CO_2 concentrations would have to be higher than currently measured, since all known sinks do not appear to be able to absorb all of the carbon produced. To account for this imbalance, we have assumed the existence of an "unknown sink" that absorbs the unaccounted-for carbon. The size of this unknown sink depends on the assumed magnitude of known sources and sinks--by definition, the unknown sink is simply: sources minus sinks minus atmospheric accumulation.

For our base cases, the size of the unknown sink was kept constant at 1.6 Pg annually based on its calculated value (from the model) for 1975-1985. However, alternative assumptions are plausible. To capture these uncertainties, two sensitivities were analyzed: (1) a high case, where the size of the unknown sink increases at the same rate as atmospheric CO_2 levels compared with preindustrial levels (this increase might occur, e.g., because the size of the unknown sink is related to the fertilization of terrestrial ecosystems by increasing CO_2); and (2) a low case, where the size decreases to zero exponentially at 2% per year (e.g., because the process responsible for the unknown sink has a limited capacity).

When the unknown sink is assumed to increase in proportion to CO_2 concentrations in the RCW case, the amount of carbon absorbed by the unknown sink increases to 11.6 Pg annually by 2100. This rate of carbon absorption results in a decline in CO_2 concentrations relative to the

Rapidly Changing World, which reduces realized warming by 0.1-0.2°C in 2050 and 0.5-0.7°C in 2100; equilibrium warming is reduced in 2050 by 0.2-0.5°C and in 2100 by 0.7-1.4°C (based on 2.0-4.0°C climate sensitivities).

In the low case, that is, when the unknown sink decreases to zero, the estimated impact on warming is significantly lower, since the unknown sink was only 1.6 Pg annually to start. As a result, CO_2 concentrations do increase, but the increase in realized warming is less than 0.1°C in 2050 and 0.1-0.2°C in 2100 (based on 2.0-4.0°C climate sensitivities; see Figure 6-11).

Amount of CO_2 From Deforestation

Estimates of the amount of CO_2 emitted from deforestation activities vary due to different assumptions on the rate of deforestation, the fate of the deforested lands, and the amount of carbon contained in the forest vegetation and soils. In the base cases we used the lower carbon estimates (i.e., lower biomass estimates) given by Houghton (1988); for 1980 the resulting net flux of carbon to the atmosphere was about 0.4 Pg of carbon. Higher estimates of initial biomass have also been analyzed by Houghton (1988); with these estimates the net flux of carbon to the atmosphere in 1980 would have been about 2.2 Pg. These higher biomass estimates are evaluated here for the three deforestation scenarios discussed in Chapter V. The net flux of carbon for each of these scenarios is presented in Figure 6-12.

In the RCW case the rate of CO_2 emissions from deforestation was based on an exponential decline in forest area using the lower biomass assumptions. If the higher biomass estimates are used, the total carbon flux from deforestation from 1980 to 2100 is 281 Pg compared with 118 Pg using the low estimates of carbon stocks (Houghton 1988). Similarly, in the population-based deforestation scenario the total carbon flux to the atmosphere from 1980 to 2100 is about 138 Pg using the lower

FIGURE 6-11

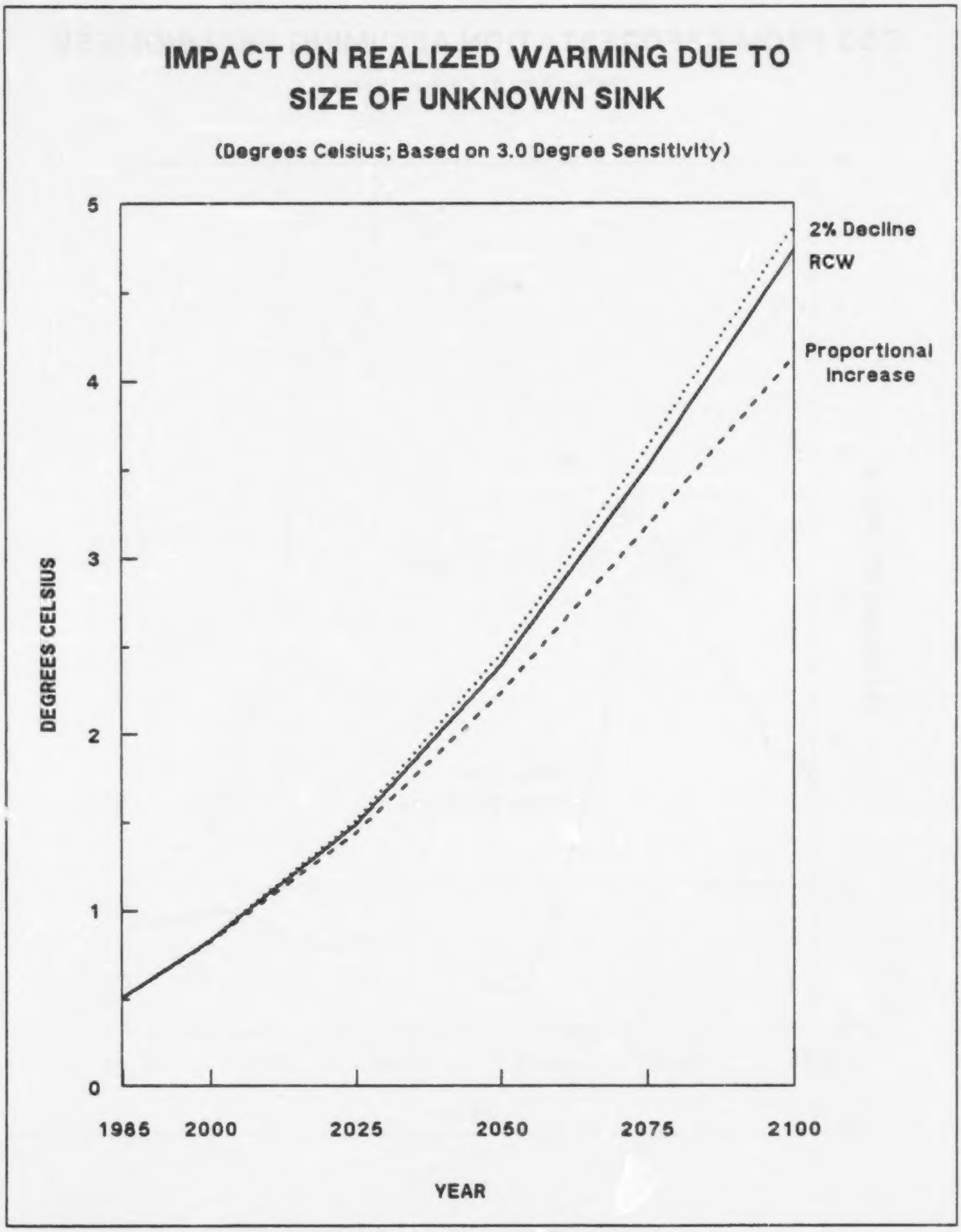
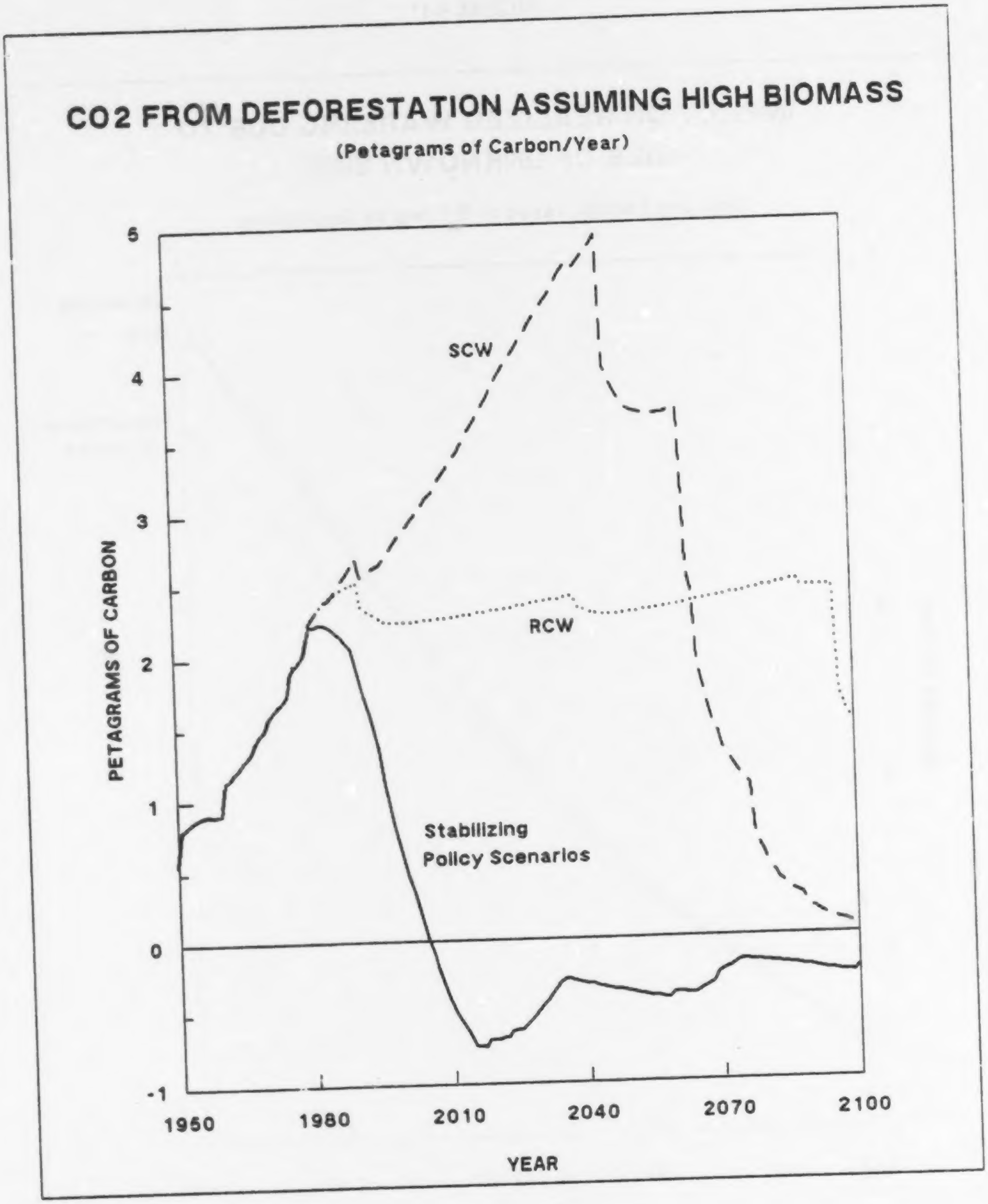

IMPACT ON REALIZED WARMING DUE TO SIZE OF UNKNOWN SINK
(Degrees Celsius; Based on 3.0 Degree Sensitivity)
DEGREES CELSIUS
0
1
2
3
4
5
1985
2000
2025
2050
2075
2100
YEAR
2% Decline
RCW
Proportional Increase

FIGURE 6-12


CO2 FROM DEFORESTATION ASSUMING HIGH BIOMASS
(Petagrams of Carbon/Year)
PETAGRAMS OF CARBON
5
4
3
2
1
0
-1
SCW
RCW
Stabilizing
Policy Scenarios
1950
1980
2010
2040
2070
2100
YEAR

biomass estimates and 324 Pg using the higher biomass estimates. In the reforestation scenario, the total accumulation of carbon from the atmosphere was 38 Pg using the lower biomass estimates and 59 Pg using the higher biomass estimates.

Despite the substantial increase in the amount of carbon from deforestation when the higher biomass estimates are used (e.g., by 2050 CO_2 emissions from deforestation are 2.3 Pg compared with 1.0 Pg in the RCW with the lower estimates), the resulting atmospheric concentration of CO_2 is only slightly higher (see Figure 6-13 for the differences in the RCW case, i.e., forest area declines exponentially). This result is due to the larger size of the "unknown carbon sink" in our model when higher deforestation emissions are assumed (see **Unknown Sink** above). In our analysis the increase in the size of the unknown sink was sufficient to absorb some of the additional carbon when the higher biomass estimates are used, assuming that the size of the unknown sink remains constant at its average 1975-1985 value (i.e., 2.6 Pg C with high biomass vs. 1.6 Pg C with low biomass). The additional increase in CO_2 increased realized warming and equilibrium warming less than 0.1°C by 2100 compared with the RCW case warming (assuming 2.0-4.0°C climate sensitivities).

Alternative CO_2 Models of Ocean Chemistry and Circulation

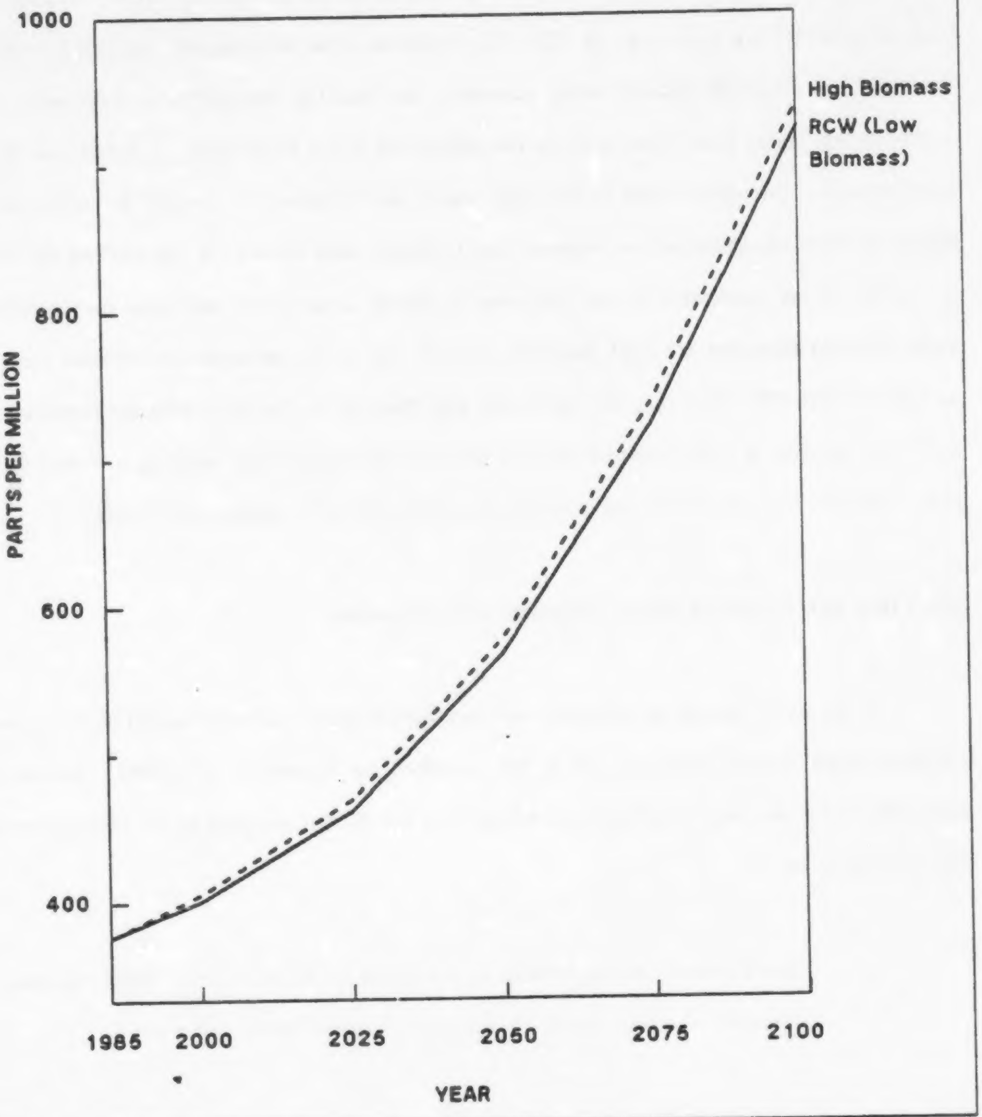
In the RCW case ocean chemistry was represented using a diffusion model of the ocean (the Modified GISS model) based on the model described by Hansen et al. (1988). Several other approaches have also been developed and adopted for the EPA framework by W. Emmanuel and B. Moore. These include:

- Box-Diffusion Model introduced by Oeschger et al. (1975), which represents the turnover of carbon below 75 meters as a purely diffusive process.

FIGURE 6-13

IMPACT OF HIGH BIOMASS ASSUMPTIONS ON ATMOSPHERIC CONCENTRATION OF CO2

(Parts Per Million; Based on 3.0 Degree Celsius Sensitivity)



- 12-Compartment Regional Model by Bolin et al. (1983), which divides the Atlantic and Pacific-Indian Oceans into surface-, intermediate-, deep-, and bottom-water compartments and divides the Arctic and Antarctic Oceans into surface- and deep-water compartments.

- Advective-Diffusive Model by Bjorkstrom (1979), which divides the surface ocean into cold and warm compartments; water downwells directly from the cold surface compartment into intermediate and deep layers.

- Outcrop-Diffusion Model by Siegenthaler (1983), which allows direct ventilation of the intermediate and deep oceans at high latitudes by incorporating outcrops connecting all sublayers to the atmosphere.

Because each of these models uses a different approach to evaluate ocean chemistry, the resulting impact on atmospheric CO_2 concentrations could vary from one approach to the next. To determine how comparable these models were, the RCW case was evaluated using each model in turn.

The estimates of future CO_2 concentrations from each model are summarized in Figure 6-14a. These results indicate that the Modified GISS model tends to project higher atmospheric CO_2 concentrations than the other models; for example, by 2100 CO_2 concentrations are about 6-7% higher than concentrations estimated by Oeschger et al., Bolin et al., or Bjorkstrom, and about 19% higher than those estimated by Siegenthaler. There are two basic reasons for these differences: (1) The Modified GISS model, unlike the other models, incorporates temperature feedback that alters ocean carbonate chemistry; that is, as the mixed layer of the oceans warms due to atmospheric warming, the amount of carbon that can be absorbed by the oceans decreases; and (2) The Modified

GISS model does not incorporate any heat or CO_2 transfer between the thermocline and the deep ocean (below 1,000 meters); to the extent heat or CO_2 is transported to the ocean depths in the long run, the Modified GISS model understates the oceans' absorption capacity.

Siegenthaler's Outcrop-Diffusion Model estimates lower CO_2 concentrations than any of the other models. This result is anticipated because the Outcrop-Diffusion Model allows CO_2 to be absorbed from the atmosphere to the deep layers rather than diffuse through the intervening layers, so that, in this model, carbon is absorbed more quickly in the oceans than in the other models. By 2100 equilibrium warming using Siegenthaler's model is 0.6-1.2°C lower than the RCW case (see Figure 6-14b for warming estimates from all five models).

ASSUMPTIONS ABOUT CLIMATE SENSITIVITY AND TIMING

Sensitivity of the Climate System

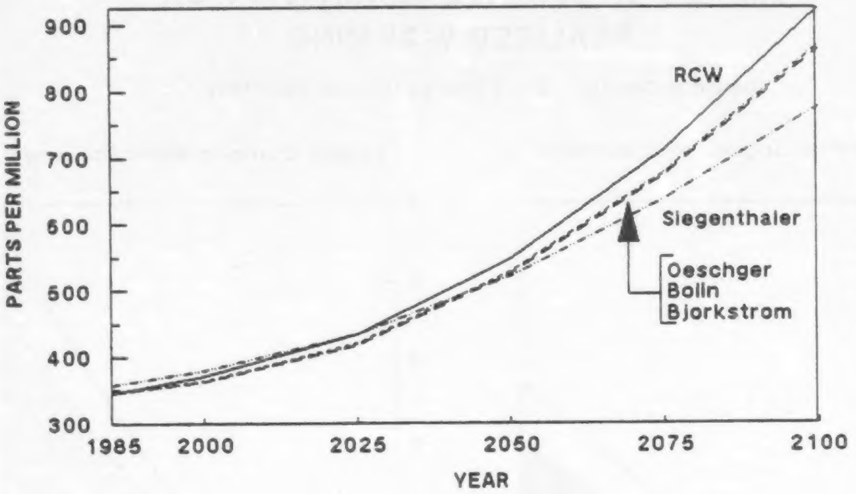
A general benchmark for comparing atmospheric models is their response to a doubling of CO_2 concentrations ($2xCO_2$; see Chapter III). Put simply, this benchmark describes how much warming would be expected once the atmosphere stabilizes following a two-fold increase in CO_2 concentrations. In our analyses we have used the range from 2.0-4.0°C. As discussed in Chapter III, there is a great deal of uncertainty about the strength of internal climate feedbacks, and, in some cases, whether a feedback will be positive or negative. If cloud and surface albedo changes produce large positive feedbacks, as suggested by some analyses, the climate sensitivity could be 5.5°C or greater. On the other hand, these feedbacks could be weak and cloud feedbacks could be negative, resulting in a climate sensitivity as low as 1.5°C. For the sensitivity analysis, therefore, we have evaluated the extent of global warming using 1.5 and 5.5°C as lower and upper bounds, respectively. The impact of these assumptions on realized warming is summarized in Figure 6-15 for the RCW

FIGURE 6-14

COMPARISON OF DIFFERENT OCEAN MODELS

CO2 CONCENTRATIONS

(Parts Per Million)



IMPACT ON EQUILIBRIUM WARMING

(Based on 3.0 Degree Celsius Sensitivity)

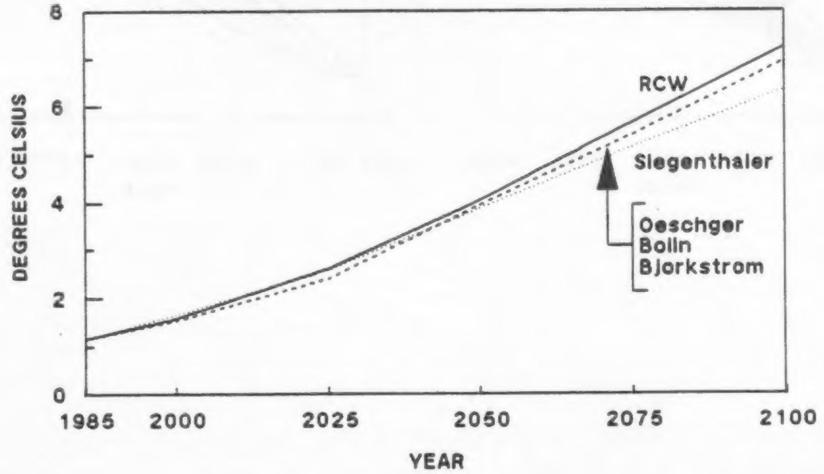
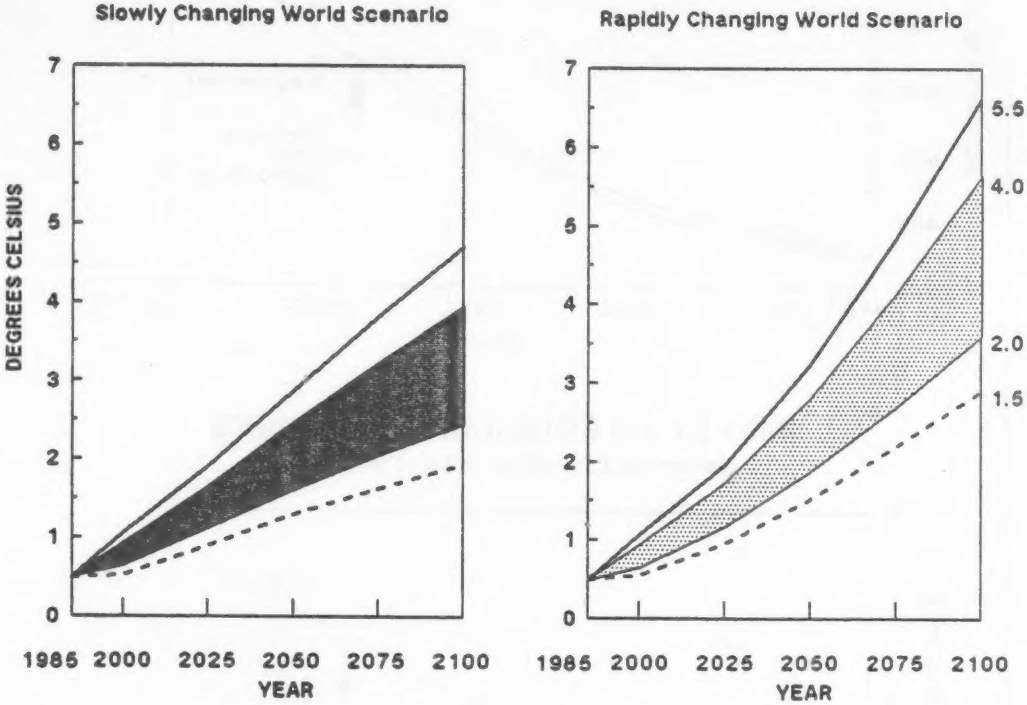


FIGURE 6-15

IMPACT OF CLIMATE SENSITIVITY ON REALIZED WARMING

(Degrees Celsius; 1.5-5.5 Degree Climate Sensitivity)


Slowly Changing World Scenario

Rapidly Changing World Scenario

and SCW cases. In the RCW case, the range of realized warming for a 1.5-5.5°C climate sensitivity would be 1.5-3.2°C by 2050 and 2.9-6.6°C by 2100, compared with a range of 1.9-2.8°C by 2050 and 3.6-5.6°C by 2100 when the climate sensitivity is bounded by 2.0-4.0°C. The corresponding values for equilibrium warming for a 1.5-5.5°C climate sensitivity are 2.0-7.4°C by 2050 and 3.6-13.2°C by 2100, compared with 2.7-5.4°C by 2050 and 4.8-9.6°C by 2100 for a 2.0-4.0°C climate sensitivity. In the SCW case, the range of realized warming for a 1.5-5.5°C climate sensitivity would be 1.3-2.9°C by 2050 and 2.0-4.7°C by 2100, compared with a range of 1.6-2.5°C by 2050 and 2.5-4.0°C by 2100 when the range of climate sensitivity is 2.0-4.0°C. The corresponding values for equilibrium warming for a 1.5-5.5°C climate sensitivity are 1.7-6.1°C by 2050 and 2.4-8.6°C by 2100, compared with 2.2-4.5°C by 2050 and 3.1-6.3°C for a 2.0-4.0°C climate sensitivity.

Rate of Heat Diffusion

CO_2 and heat are currently transferred from the atmosphere to the oceans and within the ocean itself as a result of many complex chemical and physical interactions. One of these interactions is the transfer of heat from the mixed layer to the thermocline, thereby delaying global warming. Additionally, changes in ocean mixing and circulation patterns as a result of climate change could alter the capacity of the oceans to absorb heat (see **BIOGEOCHEMICAL FEEDBACKS** for further discussion). The rate at which heat is absorbed only affects the rate of realized warming, not the rate of equilibrium warming, because the oceans cannot absorb heat indefinitely.

In our model the rate at which mixing occurs between the mixed layer and the thermocline is parameterized with an eddy-diffusion coefficient (see Chapter III). The value of the eddy-diffusion coefficient in the base cases was assumed to be 0.55×10^{-4} m^2/sec. For purposes of this sensitivity analysis alternative values of 2×10^{-5} and 2×10^{-4} have been evaluated.

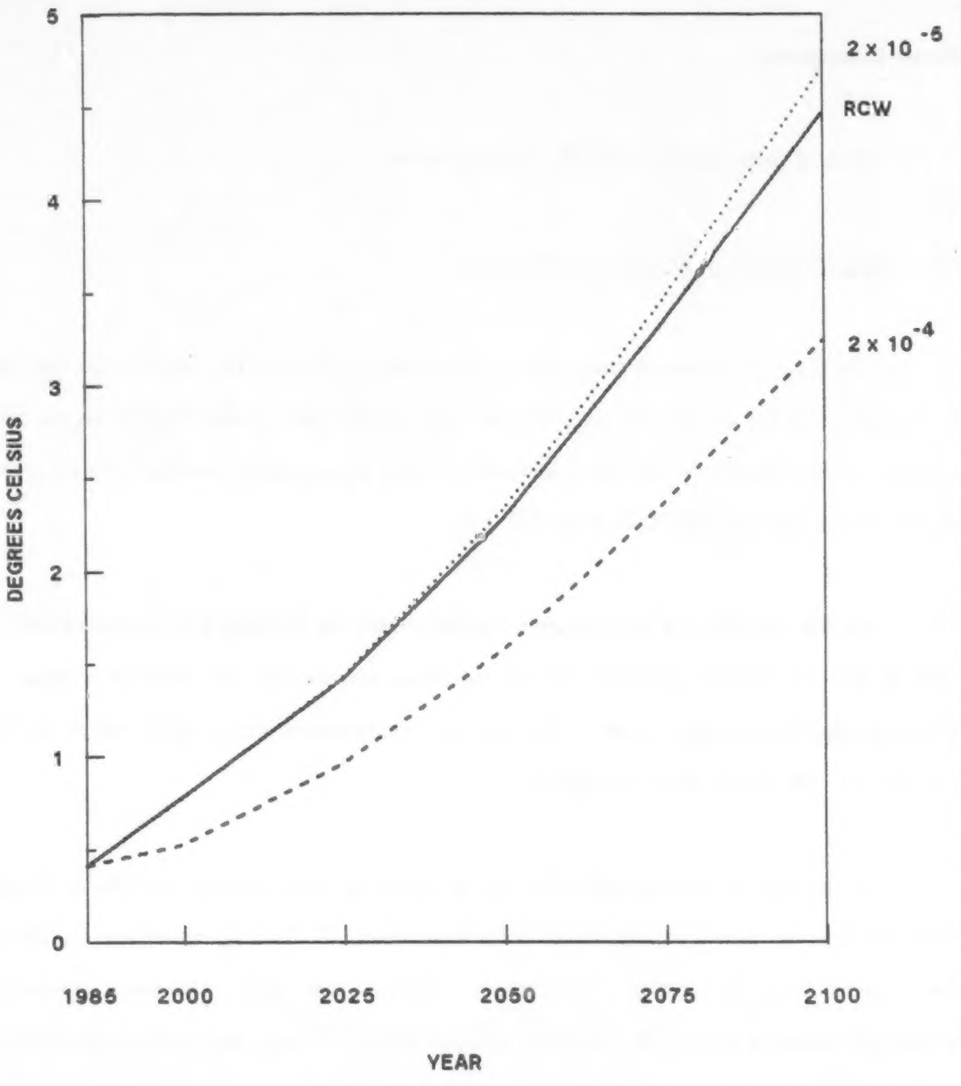
As shown in Figure 6-16 the rate at which the oceans absorb heat can noticeably affect the amount of realized warming by 2100. If the rate of heat absorption is greater than that assumed in the base cases (i.e., if the eddy-diffusion coefficient is 2×10^{-4} m^2/sec), realized warming by 2100 would be 0.5-1.2°C less than in the RCW case (assuming 2.0-4.0°C climate sensitivities). For the smaller eddy-diffusion coefficient of 2×10^{-5} m^2/sec, realized warming by 2100 would be 0.3-0.9°C higher.

ASSUMPTIONS ABOUT ATMOSPHERIC CHEMISTRY: A COMPARISON OF MODELS

As discussed in Chapters II and III, the chemistry of the future troposphere is one of the uncertainties in the prediction of atmospheric composition. The principal factors contributing to this uncertainty are: (1) the complexity and tremendous natural variability of chemistry in the troposphere, especially regarding oxidant formation; (2) the range of interactions between tropospheric chemistry and radiation perturbed by climate change and changes in stratospheric composition; and (3) the range of uncertainties in future emissions of CH_4, CO, NO_x, and non-methane hydrocarbons (NMHC). This section focuses on the first two aspects of uncertainty in atmospheric composition.

Recognizing the uncertainty in tropospheric chemistry, EPA sponsored a workshop on atmospheric composition to discuss recent modelling efforts among members of the atmospheric sciences community and to construct a parameterized atmospheric chemistry model that would incorporate the latest scientific findings. The end result was the Assessment Model for Atmospheric Composition (AMAC), the model used to obtain the findings discussed in this report. AMAC was developed by Prather of NASA/GISS as a result of the workshop, which was held in January 1988 (see Prather, 1988). To obtain insight into the uncertainties introduced by the physical simplifications made by the AMAC and to ensure results that are comparable to current, more-detailed modeling

FIGURE 6-16



CHANGE IN REALIZED WARMING
DUE TO RATE OF OCEAN HEAT UPTAKE
(Degrees Celsius; Based on 3.0 Degree Sensitivity)

efforts, a set of common scenarios of CH_4, CO, and NO_x emissions were analyzed in the AMAC, as well as in two current research models: a 2-D tropospheric chemistry model developed by Isaksen (Isaksen and Hov, 1987); and a multi-box photochemical model of the global troposphere developed by Thompson and co-workers at NASA/Goddard (Thompson et al., 1988).

Model Descriptions

Each of these models is briefly described below.

Assessment Model for Atmospheric Composition

The focus of interest in tropospheric composition is on O_3, CH_4, and OH, because the two former gases are key greenhouse absorbers and OH (together with ozone) determines the oxidizing capacity of the atmosphere and the abundance of many gases such as methane, carbon monoxide, methyl chloroform, and HCFC-22 (CHF_2Cl).

For the simulation of the troposphere in this model, the Northern and Southern Hemispheres (NH & SH) are treated separately because significant asymmetries are observed in many of the important shorter-lived gases, such as CO and NO_x. These species play a major role in the budgets for CH_4, O_3, and OH in each hemisphere.

In the AMAC, tropospheric OH can be treated as a steady-state variable as it responds immediately to the annual average values of the trace gases. To derive perturbations to OH, a non-linear system is solved equating a "production" term to a "loss" term. OH losses are partitioned among the predicted gases (CH_4, CO), the specified fluxes (NMHC), and self-reactions (OH). The production side of the equation includes a positive response to increases in UV radiation (i.e., loss in column ozone) and in tropospheric H_2O, O_3, and NO_x fluxes. Coefficients for variations in either the production or loss terms with respect to column O_3, tropospheric water vapor, trop-O_3, CO, CH_4, and fluxes of both NMHCs and NO_x are based on results from 1-D and 2-D models (Liu et al., 1987; Thompson and Cicerone, 1986; Isaksen and Hov, 1987; Isaksen et al., 1988). Major sources of uncertainty in calculating OH are the spatial averaging for this highly variable constituent and the nonlinearity in perturbation coefficients, especially with respect to NO_x distribution.

Perturbations to tropospheric ozone affect both tropospheric temperatures and the long-lived source gases controlled by OH. A significant fraction of tropospheric ozone originates in the stratosphere and is destroyed by surface deposition; it is sufficiently short-lived (a few months) that the AMAC calculates ozone perturbations separately for each hemisphere. Changes in tropospheric ozone are associated with perturbations to the total ozone column, and to tropospheric chemical reactions, which are evaluated with sensitivity coefficients, $d\ln(O_3)/d\ln(X)$, ascribed to the precursor gases (Column -O_3, 0.8; CH_4, O.2; CO, O.1; NO_x flux, O.1; NMHC flux, O.1). The coefficients are based on detailed photochemical models for typical tropospheric air parcels (Liu et al., 1987; Thompson et al., 1988), but their uncertainties are large, approximately a factor of 2. Also, the efficiency of O_3 production varies widely with the NO_x levels (Liu et al., 1987), which in turn cannot be adequately characterized throughout the entire troposphere due to their large dynamic range. A similar concern applies to the simplified treatment of non-methane hydrocarbons.

Isaksen Model

The Isaksen model is a 2-D transport model that calculates absolute concentrations for O_3 and OH (and several dozen other trace chemical constituents in the troposphere) as functions of altitude and latitude, as emissions are varied over time (Isaksen and Hov, 1987; Isaksen et al., 1988). Unlike the AMAC, this model resolves latitudinal and altitude distributions, and emission changes are introduced with latitudinal discrimination. The transport of longer-lived constituents can locate key areas of tropospheric ozone and OH change that the AMAC will miss; because a 2-D model resolves altitude, the effects of high-altitude aircraft emissions on NO_x and ozone or cloud perturbations to radiation fields, for example, can be explored. The Isaksen model differs from the AMAC in that the troposphere is not coupled to the stratosphere, so that the impact of changing climate or perturbations on stratospheric ozone are not included. Methane flux changes are included in annual updates of the model.

Thompson et al. Model

The Thompson model couples the result of 1-D model calculations of the time history for eight chemically coherent global regions, which are then averaged to estimate net global changes. A steady-state method is used: emissions are specified in simulations to represent conditions at 5-year intervals. This is somewhat inadequate for lifetime changes, tending to underestimate tropospheric ozone increases (up to 30% in one test case) and to overestimate increases in CH_4 concentrations.

The description of chemically coherent regions offers insight into regional variability, a feature lacking in the version of the Isaksen model used here, which does not have the longitudinal variation needed to treat emissions that are restricted to the source area but that can have extensive effects on ozone and OH. Like the Isaksen model, the Thompson model includes a more complete set of chemical constituents than does the AMAC and can identify other effects and interactions of climate perturbation. For example, the oxidants that contribute to sulfuric acid formation in clouds and rain (HO_2 and H_2O_2) are very sensitive to changes in stratospheric ozone and tropospheric water vapor. At the 2035 year point, stratospheric ozone depletion and climate change (temperature and water vapor) effects are added to calculations with perturbed CH_4, CO, and NO_x emissions.

Results from the Common Scenarios

It is not easy to compare the models because the structure, input, and derived quantities from the three models are not treated comparably. Nevertheless, insights into uncertainties can be obtained by comparing selected results from each model. EPA supplied eight scenarios of alternative estimates of CH_4, CO, and NO_x for evaluation in each model. In this section one of these scenarios is discussed (EPA Scenario #2), which assumes low CH_4, low CO, and high NO_x growth in sources, a rapid growth scenario for CO_2 and N_2O from combustion, and a CFC and halon scenario consistent with the Montreal Protocol. Table 6-4 summarizes the emission estimates for this scenario and compares them to estimates from the Rapidly Changing World (RCW) and Slowly Changing World (SCW) scenarios (Appendix C provides more detail for all eight scenarios). The RCW and SCW cases could not be explicitly included for this model comparison because the development of these cases occurred simultaneously with the model comparison. Table 6-5 summarizes the results for all eight scenarios.

The EPA #2 emission estimates are in the same range as those of the other two cases except for CO emissions. These estimates are much lower than both the RCW and SCW cases and are similar to the Stabilizing Policy cases due to stringent control assumptions on transport vehicle emissions. For the other emissions, the CO_2 emission estimates in EPA #2 fall between the RCW and SCW cases for most of the time periods, approaching the RCW estimates by 2100. The CH_4 and NO_x estimates are similar to those for the SCW case, except that NO_x estimates after 2050 fall between the RCW and SCW estimates.

The AMAC's troposphere is basically a parameterized 2-box model: it reports mean tropospheric values (ppb) for CH_4, and separate perturbations (% change) to OH and O_3 in each hemisphere. For the global average perturbation to OH and O_3, Northern and Southern Hemisphere

TABLE 6-4

Comparison of Emission Estimates For EPA #2, RCW, and SCW cases

(in teragrams, unless indicated otherwise)

	Emissions Estimates by Year					
Trace Gas	1985	2000	2025	2050	2075	2100
CO_2 (Pg C)						
EPA #2	6.3	7.3	10.4	13.7	17.9	25.2
RCW	5.9	7.6	11.5	16.6	22.2	25.5
SCW	5.9	7.2	9.2	9.8	9.7	11.4
CO (as C)						
EPA #2	316	226	194	192	178	192
RCW	502	571	699	895	1050	1207
SCW	502	616	842	859	595	604
CH_4						
EPA #2	500	548	640	721	779	809
RCW	510	577	712	880	1025	1089
SCW	510	569	676	740	773	816
NO_x (as N)						
EPA #2	59	59	64	72	82	104
RCW	53	60	73	92	108	118
SCW	53	59	69	71	65	70

TABLE 6-5

Comparison of Results From Atmospheric Chemistry Models for the Year 2050 Compared to 1985

Model	Test Case Results			
	LOW CH_4		HIGH CH_4	
	Low CO	High CO	Low CO	High CO
Increases in Methane (ppb)				
Low NO_x	EPA#1	EPA#3	EPA#5	EPA#7
Prather	806	1031	1750	2022
Isaksen	400	720	950	1220
Thompson et al.	750	1000	1710	1890
High NO_x	EPA#2	EPA#4	EPA#6	EPA#8
Prather	801	1048	2082	2242
Isaksen	350	550	1010	1200
Thompson et al.	870	1240	2210	2560
Percent Change in CO				
Low NO_x	EPA#1	EPA#3	EPA#5	EPA#7
Prather	16	43	55	82
Isaksen	-13	8	0	17
Thompson et al.	-10	25	16	52
High NO_x	EPA#2	EPA#4	EPA#6	EPA#8
Prather	17	44	70	99
Isaksen	-9	8	8	19
Thompson et al.	-2.4	58	35	97

TABLE 6-5 (continued)

Comparison of Results From Atmospheric Chemistry Models for the Year 2050 Compared to 1985

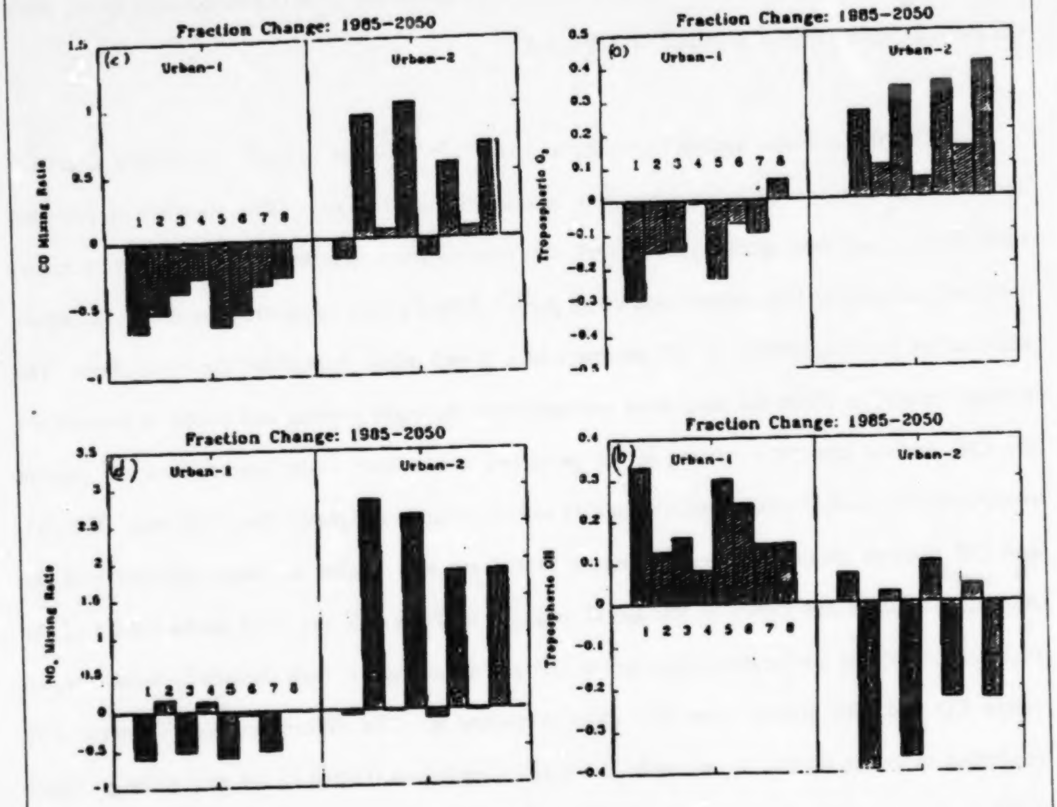
Model	Test Case Results			
	LOW CH_4		HIGH CH_4	
	Low CO	High CO	Low CO	High CO
Percent Change in OH				
Low NO_x	EPA#1	EPA#3	EPA#5	EPA#7
Prather	-9	-14	-23	-26
Isaksen	5	-1	1	-2
Thompson et al.	-9.4	-15.5	-20.1	-27.6
High NO_x	EPA#2	EPA#4	EPA#6	EPA#8
Prather	-2	-9	-22	-25
Isaksen	8	4	5	3
Thompson et al.	-8.9	-17.4	-22.1	-23.9
Percent Change in O_3				
Low NO_x	EPA#1	EPA#3	EPA#5	EPA#7
Prather	1	8	21	27
Isaksen	-1	2	3	5
Thompson et al.	3.7	9.9	13.2	18.3
High NO_x	EPA#2	EPA#4	EPA#6	EPA#8
Prather	5	13	33	39
Isaksen	5	8	10	13
Thompson et al.	10.0	17.5	23.1	29.0

results are averaged with equal weight. In addition to the perturbed species discussed here with the tropospheric chemical models, the AMAC calculated other significant perturbations, such as a 12% decrease in column ozone, a 2°K rise in mean tropospheric temperature, along with a 10% increase in tropospheric water vapor. These perturbations have an impact on tropospheric OH, O_3, CO, and CH_4. Additionally, unlike the other two models, which provide point estimates, the AMAC produces a range of trace-gas scenarios in response to specified uncertainties in the model coefficients (only the mean of each range is provided in Table 6-5).

The Thompson model averages over eight "chemically coherent regions" (Appendix C gives a description of how the EPA scenarios were assigned to the regions). This approach is probably adequate for short-lived species such as OH, and possibly for tropospheric O_3. However, it makes it difficult to interpret CH_4 calculations, which predict different CH_4 concentrations among the boxes, when in fact the long lifetime of CH_4 ensures that it is well mixed throughout the troposphere. The methane results in Table 6-5 have been averaged over the eight regions and scaled to account for the CH_4 lifetime changes occurring in the perturbed atmosphere. Also summarized are percent changes in CO (surface mixing ratios) and OH and O_3 (column-integrated from 0-15 km). The CH_4 and CO changes obtained by the Thompson model are very similar to those obtained with the AMAC. Although not shown in the global averages in Table 6-5, the most useful results of the regional calculations are localized estimates of OH and O_3 changes in each chemically defined region where CO and NO_x growth rates may differ considerably. The differences between areas with controlled emissions (Urban 1) and without controlled emissions (Urban 2) are very striking (Figure 6-17).

The Isaksen model calculates perturbations as a function of latitude, altitude (0-16 km), and time of year. The increase in CH_4 is distributed uniformly throughout the troposphere as expected. There is a problem with the implementation of the EPA #2 scenario in that the CH_4 concentrations

FIGURE 6-17



REGIONAL DIFFERENCES FOR URBAN AREAS WITH DIFFERENT EMISSIONS OF CO AND NO

Source: Thompson, 1988.

decline at the beginning of the model integration. This may be due to the low estimate of global CO flux. Initial fluxes were scaled in the AMAC and Thompson models to obtain a steady-state of current concentrations. CH_4 does not recover to its initial concentration for at least 20 years into the scenario, and this is probably the reason for the Isaksen model predicting such a small increase in CH_4. The patterns for OH and O_3 perturbations are distinct (Figure 6-18). The greatest changes in O_3 are below 2 km altitude: there is a large increase between 0° and 35°N and a small decrease centered at 50°N. The spatial pattern of changes in OH are interesting: in the upper troposphere between 12 and 16 km the OH increases by 10-30% in the Northern Hemisphere, whereas throughout most of the Southern Hemisphere OH decreases. Both of these changes may be driven by increases in CH_4. In the dry upper troposphere in the presence of NO_x, CH_4 increases the OH concentration during its atmospheric oxidation, but in the lower troposphere the CH_4 provides merely a sink for OH.

Overall, all three models predict similar increases in tropospheric O_3. The Thompson et al. and AMAC models predict decreases in tropospheric OH, while the Isaksen model reports a globally averaged increase. This discrepancy may be explained by the large increases in OH above 12 km as noted above, something that is also calculated by the Thompson model. However, most of the difference in OH levels seems attributable to the lower CO and CH_4 concentrations calculated by Isaksen compared with the other two models. As shown in Table 6-5 for all eight scenarios, none of the increases in CO by 2050 are more than 15-20% in Isaksen, whereas Thompson et al. and AMAC show CO increases up to 100% (see scenario #8). Some of the CO and OH differences between Isaksen et al. and the other two models are due to the difference in initialization described above, but most of the OH difference may be due to how CO behaves in each model. This may be one of the more prominent uncertainties in predicting future tropospheric composition. CO has a moderate lifetime (typically about a few months) with considerable spatial variability that is not well

FIGURE 6-18

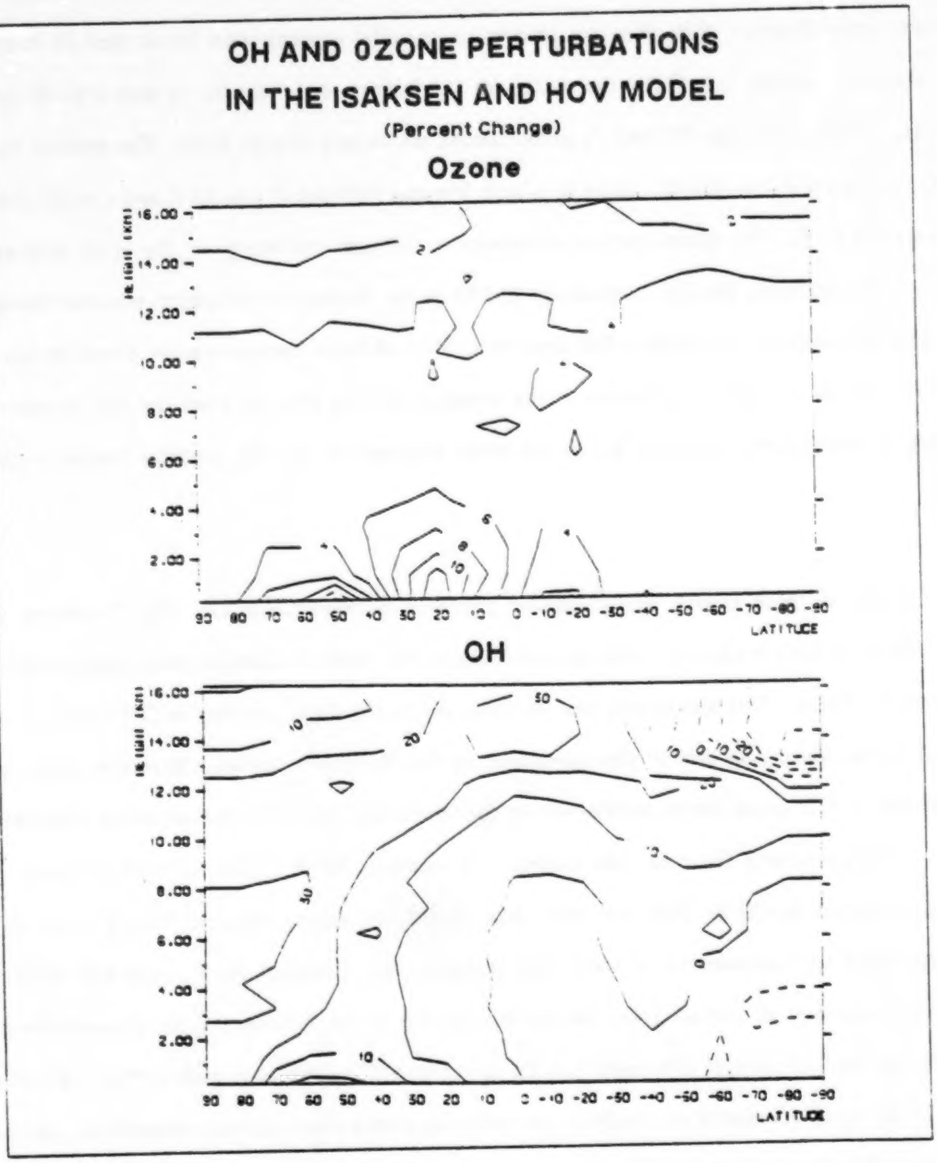


Figure 6-18. Perturbation in O_3 and OH from the Isaksen model using the EPA #2 emission estimates. Solid line indicates an increase in the parameter; dashed line indicates a decrease. O_3 shows large increase between 0° and 35°N; OH shows increases up to 30% in Northern Hemisphere, and decreases in Southern Hemisphere. Source: Isaksen and Hov, 1987.

resolved in any of the models. Perhaps the Isaksen model gives a lower limit to CO and OH changes, and the other two models estimate the largest expected changes.

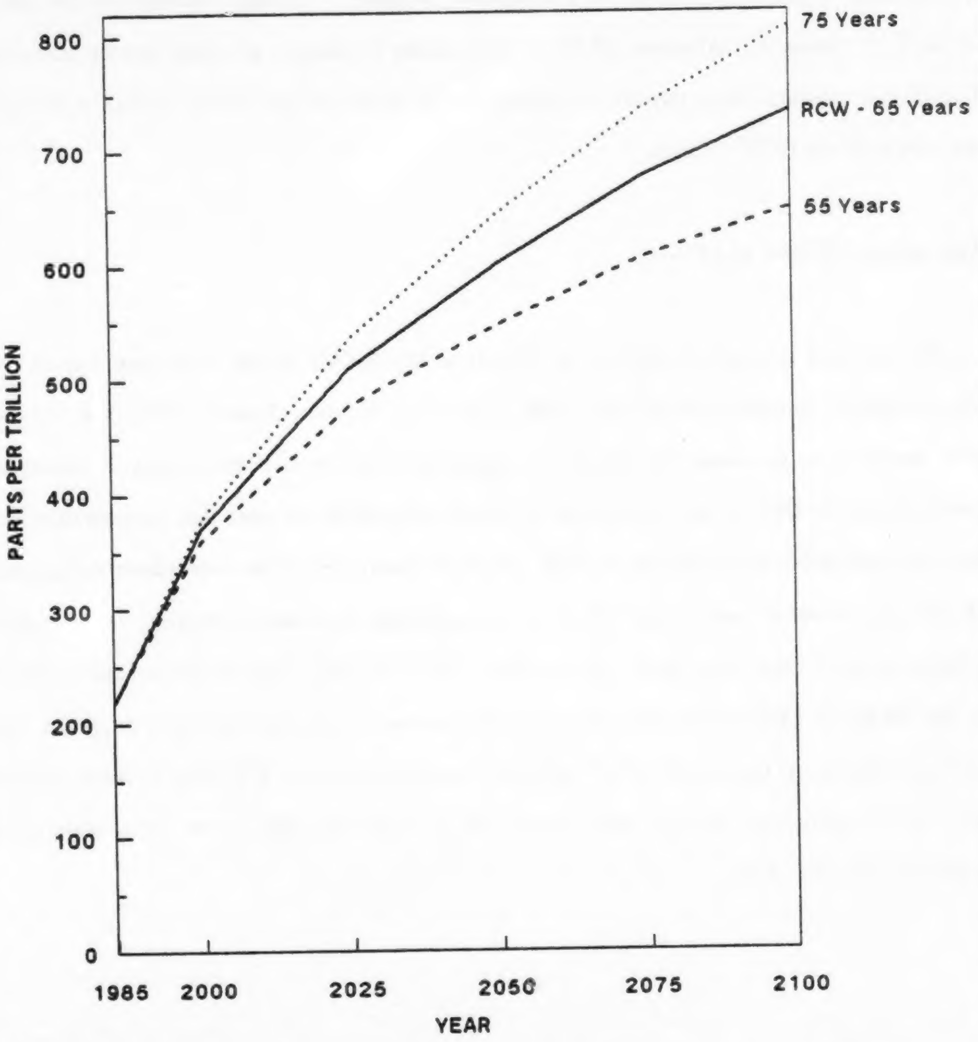
EVALUATION OF UNCERTAINTIES USING AMAC

Comparing the results of AMAC to other models given identical scenarios provides one approach to evaluating uncertainties related to atmospheric chemistry. Valuable information can also be obtained by testing the robustness of the AMAC results to changes in critical model parameters. This section examines these impacts by varying key parameters within AMAC and then comparing the results to the RCW scenario.

Atmospheric Lifetime of CFC-11

The assumed atmospheric lifetime for CFC-11 in the AMAC for the RCW case was 65 years. Its atmospheric lifetime, however, may range from 55 to 75 years (Prather 1988); these estimates were evaluated to determine the impact on atmospheric chemistry. The changes in atmospheric concentration for CFC-11 are summarized in Figure 6-19, which indicates that concentration levels may vary from about 650 to 810 ppt by 2100. Increases (decreases) in the atmospheric concentration of CFC-11, however, tend to be offset by corresponding decreases (increases) in atmospheric concentrations of other trace gases, such as other CFCs and CH_4. That is, the increase (decrease) in the lifetime of CFC-11 increases (decreases) the amount of stratospheric ozone depletion, which increases (decreases) the amount of UV radiation; these higher (lower) UV levels increase (decrease) the rate of destruction of these other gases. As a result, the impacts on global warming are negligible (less than 0.1°C).

FIGURE 6-19



SENSITIVITY OF ATMOSPHERIC CONCENTRATION OF CFC-11 TO ITS LIFETIME

(Parts Per Trillion; Based on 3.0 Degree Celsius Sensitivity)

Interaction of Chlorine with Column Ozone

Chlorine in the stratosphere has a negative, non-linear impact on total column ozone. This chemical interaction is one of the primary causes of stratospheric ozone depletion due to the chlorine contained in CFCs; this interaction has been included in the AMAC, however, primarily for its ability to affect the rate of tropospheric ozone formation. In the RCW case this relationship was defined as a 0.03% decline in total column ozone/(ppb)^2 of stratospheric chlorine. A higher value, 0.20%, was evaluated, which would increase the rate of column ozone destruction.

With the 0.20% assumption, total column ozone depletion was 45-47% by 2050 (assuming 2.0-4.0°C climate sensitivities) compared with a total column ozone depletion of 16.8% with the lower value (i.e., the -0.03% value used in the RCW case). The increase in total column ozone depletion has a positive feedback on the tropospheric OH levels due to the increase in UV radiation. The resulting OH interactions with other trace gases substantially reduces the atmospheric concentration of CH_4, HCFC-22, methyl chloroform, and methyl chloride, and reduces the rate of tropospheric ozone formation. (The role of O_3 is problematic, O_3 at 10-12 km probably would increase. At this altitude, O_3 probably has the largest greenhouse effect. See Chapter II) These impacts reduce the amount of global warming; as shown in Figure 6-20, the decline in realized warming is 0.1°C by 2050, compared with the RCW case, and 0.3-0.4°C by 2100; the decline in equilibrium warming by 2100 is 0.4-0.8°C (assuming 2.0-4.0°C climate sensitivities).

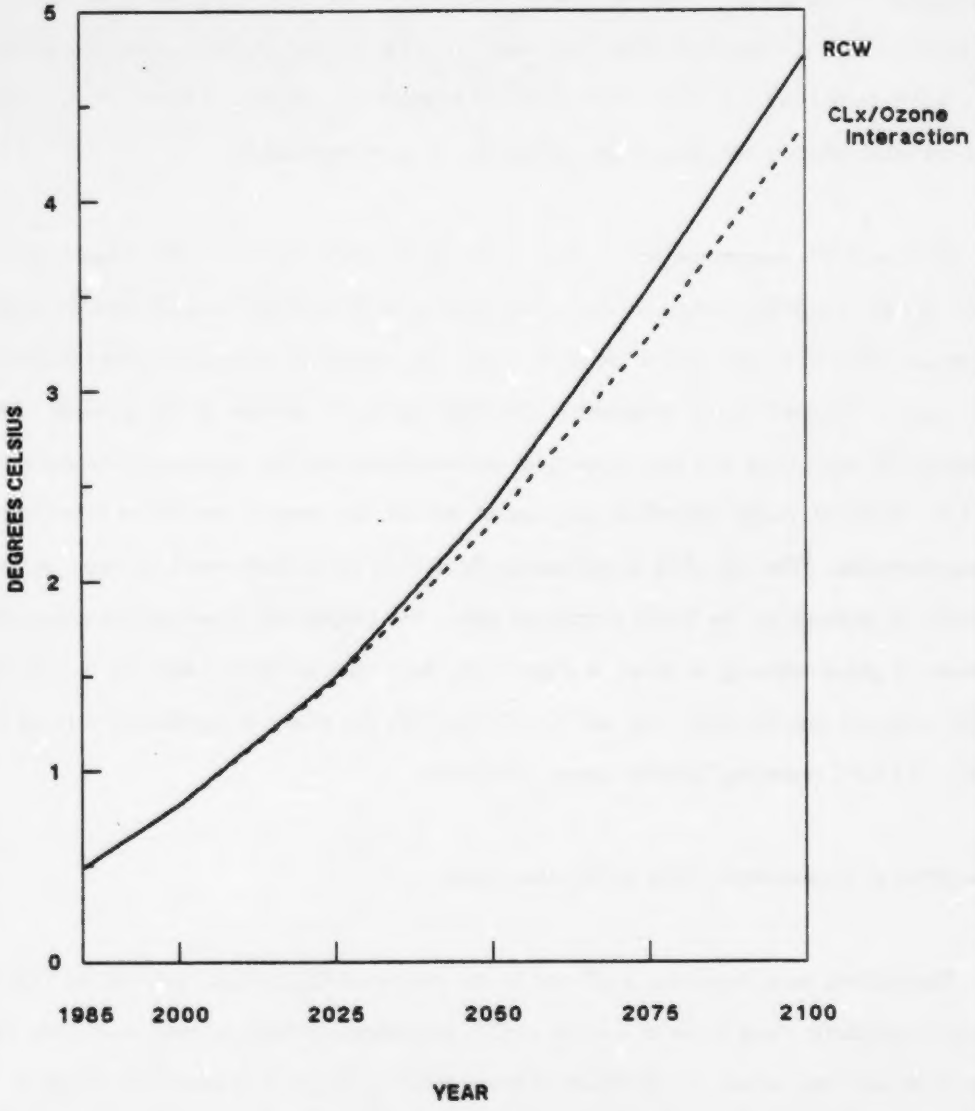
Sensitivity of Tropospheric Ozone to CH_4 Abundance

Tropospheric ozone formation is affected by the amount of CH_4 present, although the rate at which tropospheric ozone forms as a result of CH_4 abundance is subject to some uncertainty. In the RCW case, this variable for the Northern Hemisphere was assumed to be a 0.2% change in

FIGURE 6-20

CHANGE IN REALIZED WARMING DUE TO RATE OF INTERACTION OF CLx WITH OZONE

(Degrees Celsius; Based on 3.0 Degree Sensitivity)



tropospheric ozone for each percentage change in CH_4 concentration; other evidence suggests that a higher value, 0.4%, is possible (Prather, 1988).

Using this higher value increases the change in tropospheric ozone in 2100 by about 50% over the RCW case (tropospheric ozone increases by about 63% compared with about 43% when a value of 0.2% is assumed). The increase in tropospheric ozone indirectly results in a decrease in CH_4 concentrations since the tropospheric ozone increase also increases OH formation, which destroys CH_4. Due to this partially offsetting effect, the increase in global warming is less than 0.1°C.

Sensitivity of OH to NO_x

Tropospheric OH formation is affected by the level of NO_x emissions, although the rate of OH formation is uncertain. In the RCW case, we assumed a 0.1% OH change for every 1.0% change in NO_x emissions for the Northern Hemisphere. We evaluated a range of uncertainty from 0.05% to 0.2%.

An increase (decrease) in the amount of OH due to a higher (lower) sensitivity to NO_x emissions results in less (more) tropospheric ozone formation as well as lower (higher) levels of CO and CH_4. The higher sensitivity value of 0.2% reduces realized warming about 0.1°C by 2100 compared with the RCW case (assuming 2.0-4.0°C climate sensitivities; equilibrium warming is about 0.2°C lower by 2100), while the lower sensitivity value of 0.05% increases realized warming less than 0.1°C by 2100 (equilibrium warming increases a maximum of 0.1°C by 2100).

BIOGEOCHEMICAL FEEDBACKS

The sensitivity of the climate system to anthropogenic perturbations is determined by a combination of feedbacks that amplify or dampen the direct radiative effects of increasing concentrations of greenhouse gases. Several important internal climate feedbacks, such as those resulting from changes in water vapor, clouds, and sea ice albedo, are included in the estimates of climate sensitivity discussed throughout this Report. There are a number of feedbacks of a biogeochemical origin, however, that may also play an important role in climatic change that were not included in the analyses on which this range is based. Biogeochemical sources of feedback include releases of methane hydrates; changes in ocean chemistry, biology, and circulation; and changes in the albedo of the global vegetation.

Any attempt to quantify the impact of biogeochemical feedbacks is necessarily quite speculative at this time; however, it does appear that they could have an important impact on global climate. For example, Lashof (1989) has estimated that the gain from biogeochemical feedbacks ranges from 0.05-0.29 compared with a 0.17-0.77 gain from internal climate feedbacks. (The gain is defined as the portion of global equilibrium temperature change attributable to the feedback divided by the total global equilibrium temperature when the feedback is included). Some of these key feedbacks were incorporated into the AMAC for these sensitivity cases to determine the magnitude of their impact on global warming.

Ocean Circulation

As mentioned above, the oceans are currently a major sink for heat and CO_2. Concerns have been raised, however, that the basic circulation patterns that allow these processes to continue could be significantly altered as the global climate changes. This possibility is suggested by the rapid rate of atmospheric CO_2 change during past periods of climate change (e.g., see Chapter III). If circulation patterns did change, it is plausible that the oceans would no longer be a net sink for heat and CO_2.

It is not known at what point ocean circulation would be altered. For this analysis we assumed that a 2°C increase in realized warming would alter ocean circulation patterns sufficiently to shut off net uptake of CO_2 and heat by the oceans. This would increase atmospheric CO_2 concentrations from 10-25% by 2100, and would reduce the difference between realized and equilibrium warming as the atmosphere warmed more quickly due to the oceans' inability to continue to act as a heat sink. As shown in Figure 6-21, this feedback is sufficient to increase realized warming up to 1.4°C by 2050 and 1.3-3.5°C by 2100 compared with the warming estimated for the RCW case.

Methane Feedbacks

Increases in global temperature could increase the amount of CH_4 emissions due to several feedback processes: (1) release of methane from hydrates, which are methane compounds contained in continental slope sediments, as increasing temperatures destabilize the formations; (2) additional methane from high-latitude bogs due to longer growing seasons and higher temperatures; and (3) increased rate of methanogenesis from rice cultivation. The amount of CH_4 that could be released from each of these feedback processes, and the rate at which any releases might occur, are highly speculative. For each process we have assumed that the rate of CH_4 release is linearly related to the increase in temperature, with each 1°C increase leading to an additional 110 Tg from methane hydrates, 12 Tg from bogs, and 7 Tg from rice cultivation (Lashof, 1989). These methane feedbacks could have a major impact on atmospheric CH_4 concentrations: by 2100 concentrations would increase to about 7000-8350 ppb, compared with 4150-4400 ppb in the RCW case. As shown in

FIGURE 6-21

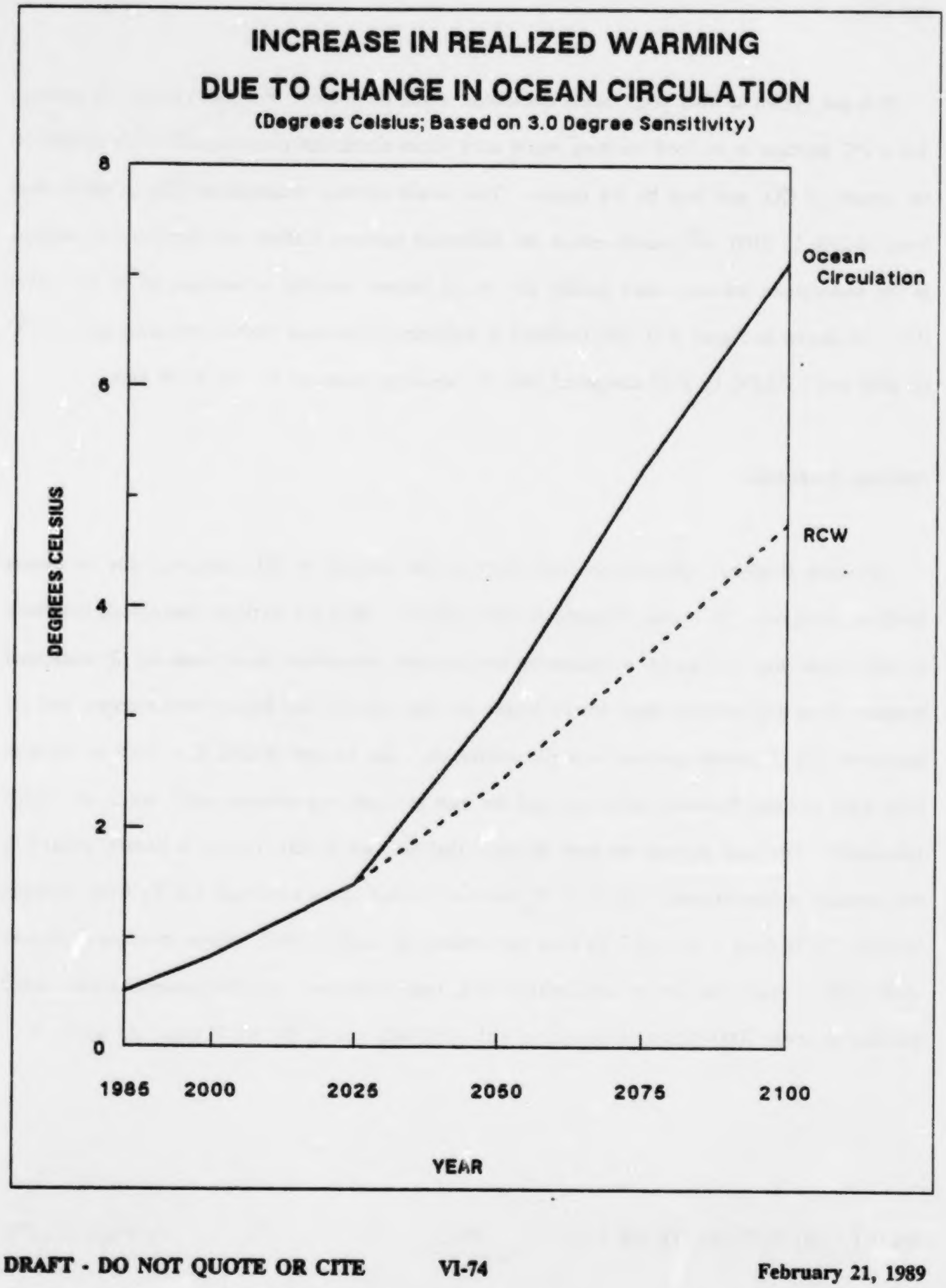

INCREASE IN REALIZED WARMING
DUE TO CHANGE IN OCEAN CIRCULATION
(Degrees Celsius; Based on 3.0 Degree Sensitivity)
DEGREES CELSIUS
8
6
4
2
0
1985
2000
2025
2050
2075
2100
YEAR
Ocean Circulation
RCW

Figure 6-22, this increase in CH_4 would be sufficient to increase realized warming relative to the RCW case about 0.2-0.4°C by 2050 and 0.4-1.0°C by 2100 (assuming 2.0-4.0°C climate sensitivities).

Combined Feedbacks

In addition to the two separate feedbacks discussed above, we analyzed the combined impact of several types of biogeochemical feedbacks. The following specific feedbacks were included: (1) methane from hydrates, bogs, and rice cultivation, as previously discussed; (2) increased stability of the thermocline, thereby slowing the rate of heat and CO_2 uptake by the deep ocean by 30% due to less mixing; (3) vegetation albedo, which is a decrease in global albedo as a result of changes in the distribution of terrestrial ecosystems by 0.06% per 1°C warming; (4) disruption of existing ecosystems, resulting in transient reductions in biomass and soil carbon at the rate of 0.5 Pg C per year per 1°C warming; and (5) CO_2 fertilization, which is an increase in the amount of carbon stored in the biosphere in response to higher CO_2 concentrations at the rate of 0.3 Pg C per ppm. See Lashof (1989) for further discussion.

The combined impact of these feedbacks on realized warming is an increase of 0.4-0.9°C by 2050 and 0.8-2.5°C by 2100 relative to the RCW case (assuming 2.0-4.0°C climate sensitivities; see Figure 6-23); the increase in equilibrium warming is 0.4-1.7°C by 2050 and 0.7-3.2°C by 2100. These preliminary analyses strongly suggest that biogeochemical feedbacks could have a major impact on the rate of climatic change during the next century.

FIGURE 6-22

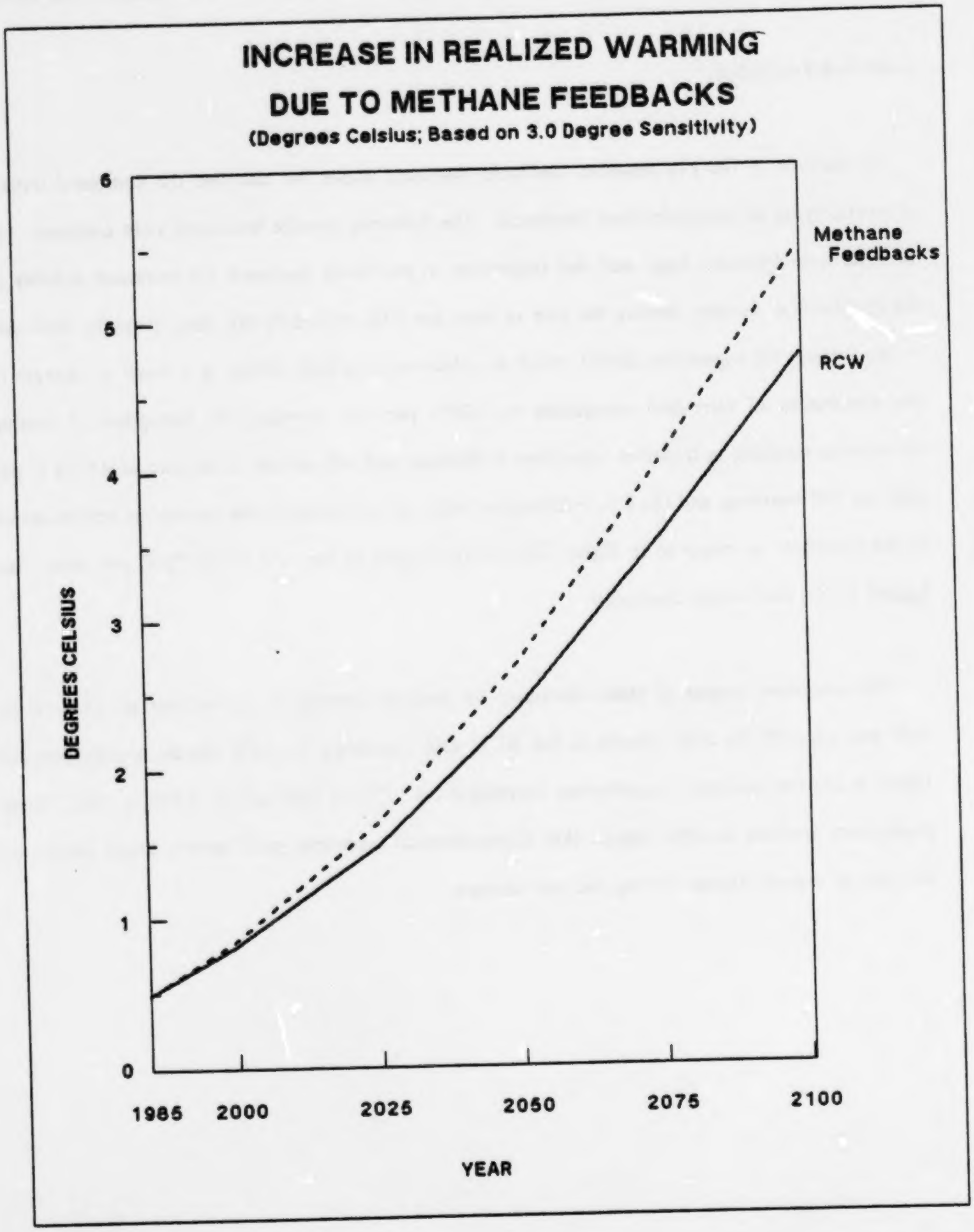
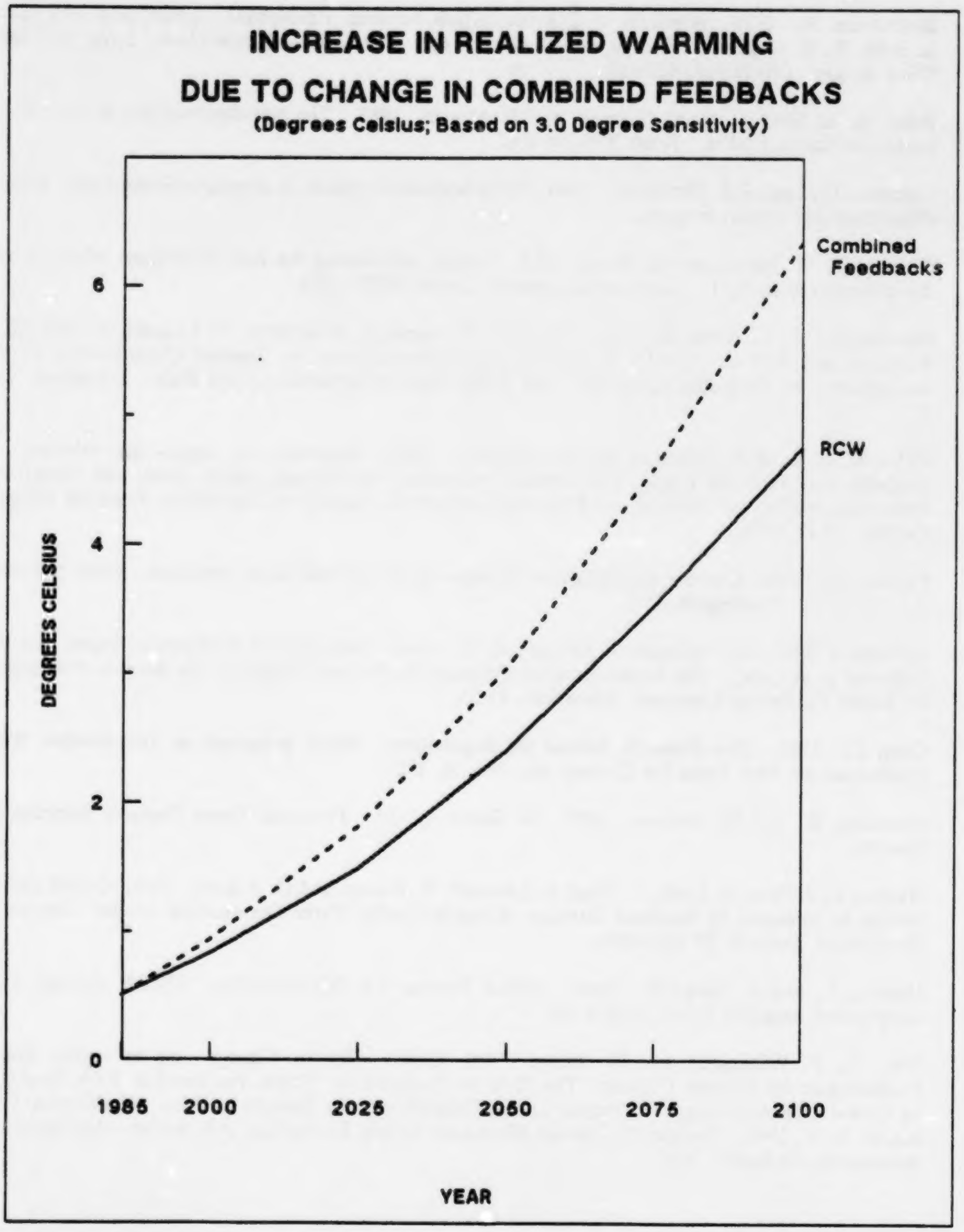

INCREASE IN REALIZED WARMING
DUE TO METHANE FEEDBACKS
(Degrees Celsius; Based on 3.0 Degree Sensitivity)
DEGREES CELSIUS
0
1
2
3
4
5
6
1985
2000
2025
2050
2075
2100
YEAR
Methane Feedbacks
RCW

FIGURE 6-23


INCREASE IN REALIZED WARMING
DUE TO CHANGE IN COMBINED FEEDBACKS
(Degrees Celsius; Based on 3.0 Degree Sensitivity)
Combined Feedbacks
RCW
DEGREES CELSIUS
0
2
4
6
1985
2000
2025
2050
2075
2100
YEAR

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